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Total Maximum Daily Load (TMDL) for Lower Snake River Total Dissolved Gas

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Total Maximum Daily Load for Lower Snake River Total Dissolved Gas

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Waterbody No. WA-33-1010 and WA-35-1010

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Acronyms and Abbreviations

Corps	U.S. Army Corps of Engineers
CRITFC	Columbia River Inter-Tribal Fish Commission
DGAS	Dissolved Gas Abatement Study
EPA	U.S. Environmental Protection Agency
FMS	Fixed Monitoring Station
fmsl	feet above mean sea level
kcfs	thousand cubic feet per second
mm Hg	Millimeters of Mercury
MOA	Memorandum of Agreement
NMFS	National Marine Fisheries Service
NPDES	National Pollutant Discharge Elimination System
TDG	Total Dissolved Gas
TMDL	Total Maximum Daily Load
WAC	Washington Administrative Code
WBID	Waterbody Identification
WRIA	Water Resource Inventory Area
303(d)	Section 303(d) of the federal Clean Water Act
7Q10	Seven-day, ten-year frequency flow
ΔP	Excess gas pressure over barometric pressure

Abstract

This Total Maximum Daily Load (TMDL) addresses total dissolved gas (TDG) in the mainstem Snake River from its confluence with the Clearwater River to its mouth at the Columbia River. Washington State has listed multiple reaches of the Lower Snake River on its federal Clean Water Act 303(d) list due to TDG levels exceeding state water quality standards. The entire reach is considered impaired for TDG. Washington State is issuing this TMDL and submitting it to the U.S. Environmental Protection Agency for its approval.

Spill events at four hydroelectric projects on the Lower Snake River elevate TDG levels far above state standards. Water plunging from a spill entrains air and carries it to a depth where hydrostatic pressure forces gas into solution at high levels. High TDG can cause "gas bubble trauma" in fish, which can cause chronic or acutely lethal effects, depending on TDG levels. A spill can be caused by several conditions. A "voluntary" spill is provided to meet juvenile fish passage goals. An "involuntary" spill is caused by lack of powerhouse capacity for river flows. An involuntary spill can result from turbine maintenance or break-down, lack of power load demand, or high river flows. Measurements of TDG levels in the pool at the upstream boundary of the TMDL area occasionally exceed standards, and appear to be related to solar heating and photosynthesis in the Lower Granite pool.

This TMDL sets a TDG loading capacity for the Lower Snake River in terms of excess pressure above ambient. Load allocations also are expressed in terms of excess pressure, with allocations for each dam's spill, pool, and for the upstream boundary. Allocations for the dams' spills must be met at compliance locations within each dam's tailrace at a specified distance below the spillway, corresponding to the end of the aerated zone. The upstream allocation must be met at the Idaho border, and the pool allocations in the forebay above each dam.

An implementation plan is provided that describes short-term compliance with the federal Endangered Species Act requirements. Long-term compliance is described for both Endangered Species Act and TMDL requirements.

Acknowledgements

The Washington State Department of Ecology wishes to acknowledge the cooperation of the following agencies in the production of this TMDL.

- The U.S. Army Corps of Engineers (Walla Walla District and Northwest Division) has provided extensive technical information for this TMDL. Large tracts of the technical analysis have been quoted or paraphrased from the Corps' Dissolved Gas Abatement Study (DGAS). This TMDL would have been much more difficult without the understanding of total dissolved gas production resulting from the DGAS study.

- The National Marine Fisheries Service has provided valuable advice and review. The Biological Opinion issued in December 2000 pursuant to the Endangered Species Act was invaluable in describing the studies that have been conducted to date, and in specifying the effects of total dissolved gas on fish.

- The U.S. Environmental Protection Agency provided assistance, both financial and technical, in the production of this TMDL.

- The Columbia River Inter-Tribal Fish Commission (CRITFC) has provided invaluable review and coordination, and staff from the Yakama, Nez Perce, Colville, Spokane, and Umatilla Tribes have also contributed to the process.

- A wide variety of other individuals have provided review and input.

Nothing in this TMDL purports to represent the technical or policy positions of any of the above agencies or organizations. This TMDL is entirely the responsibility of the Washington State Department of Ecology.

Executive Summary

Description of Waterbody, Pollutant of Concern, and Pollutant Sources

This Total Maximum Daily Load (TMDL) addresses total dissolved gas (TDG) in the mainstem Snake River from its confluence with the Clearwater River (the Idaho state line) to its mouth at the Columbia River. The state of Washington has listed multiple reaches of the Lower Snake River on its federal Clean Water Act 303(d) lists due to TDG levels exceeding state water quality standards. The entire reach is considered impaired for TDG. Washington is issuing this TMDL and submitting it to the U.S. Environmental Protection Agency for its approval.

Elevated TDG levels are caused by spill events at four hydroelectric projects on the Lower Snake River. Water spilled over the spillway of a dam entrains air. When carried to depth in the dam's stilling basin, the higher hydrostatic pressure forces air into solution. The result is water supersaturated, relative to equilibrium at the surface, with dissolved nitrogen, oxygen, and the other constituents of air.

Fish in this water may not display signs of difficulty if the higher water pressures at depth offset high TDG pressure passing through the gills into the blood stream. However, if the fish inhabit supersaturated water for extended periods, or rise in the water column to a lower water pressure at shallower depths, TDG may come out of solution within the fish, forming bubbles in their body tissues. This gives rise to gas bubble trauma, which can be lethal at high levels, or give rise to chronic impairment at lower levels. There is extensive research reported in the literature on the forms of physical damage to fish that represent the symptoms of gas bubble trauma.

Spill can occur at any time for several reasons:

- Fish passage spill (voluntary spill), conducted under the Biological Opinion in compliance with the federal Endangered Species Act.
- Spill required when flow exceeds powerhouse capacity (involuntary spill).

There are three main reasons for involuntary spill:

- The powerhouse cannot pass flood flows.
- The powerhouse is off-line due to lack of power demand.
- The powerhouse is off-line for maintenance or repair.

Dams on the Lower Snake River are run-of-the-river dams with very little storage capacity. Therefore, spills are often forced due to operational decisions at upstream storage reservoirs, such as Dworshak Dam or Idaho Power's Hells Canyon Complex.

This document describes the production of TDG at the four projects in the Lower Snake River. It presents general equations representing the production of TDG, and specific equations taking into account each project's particular physical characteristics. Any other sources of TDG in the TMDL area, such as tributaries, are considered negligible compared to the four dams. TDG is also affected by barometric pressure, wind, biological productivity (photosynthesis), and water temperature, and these influences are addressed in the TMDL.

Description of the Applicable Water Quality Standards and Numeric Target

The water quality standards for Washington have a TDG criterion of *110 percent of saturation not to be exceeded at any point of measurement.* This criterion does not apply to flows above the seven-day, ten-year frequency flow (7Q10) flood flow. In addition, special “waiver” limits for TDG have been established as a temporary special condition in Washington rules, to allow higher criteria with specific averaging periods during periods of spill for fish passage. Because the waiver limits are temporary, this TMDL addresses only the 110 percent criterion. However, the implementation plan allows compliance with waiver limits through 2010 as an interim allowance for compliance with the TMDL in the short-term.

Loading Capacity

Loading capacity for TDG has been defined in terms of excess pressure over barometric pressure (ΔP). This parameter was chosen because it can be directly linked to the physical processes by which spill generates high TDG, and it has a simple mathematical relationship to TDG percent saturation. A loading capacity of 74 mm Hg has been assigned to the Snake River in this TMDL area, based on meeting 110% saturation during critically low barometric pressure conditions.

Pollutant Allocations

Because of the unique nature of TDG, load allocations for dam spills are not directly expressed in terms of mass loading. Like loading capacity, load allocations are made in terms of ΔP defined site-specifically for each dam’s spill and pool. A load allocation is also specified for the upstream boundary of the TMDL area. The wasteload allocation under this TMDL is zero, because no NPDES-permitted sources produce TDG.

Load allocations for each pool are based on the temperature change during the pool’s time of travel under critical conditions. An analysis of wind patterns indicates that winds produce very little degassing during conditions of high temperature increase. Therefore the effect of wind-induced degassing is not included in the pool allocations. The allocation for Ice Harbor Dam is based on the upstream boundary allocation for the Lower Columbia River TDG TMDL. The allocations for the upstream boundary and for the three upstream dams are the balance of the loading capacity after the pool allocation is subtracted.

Long-term compliance with load allocations for dam spills will be at the downstream end of the aerated zone below each spillway. Distances are specified for the compliance location at each dam. As a result, the load allocation must be met in the spill from each dam individually at a specified compliance location, with allowance made for degassing in the tailrace below the spillway and above the compliance location. Compliance with the pool load allocations will be at the forebay of the downstream dam and throughout the pool, while compliance with the upstream boundary allocation will be at the Idaho state line.

Compliance with load allocations are tied to structural changes at each dam, and are intended as long-term targets. Short-term compliance will be established under the implementation plan, and will be based on operational management of spills, implementation of the "fast-track" DGAS structural modifications, and compliance with ESA requirements and TDG waiver criteria.

Margin of Safety

A margin of safety is supplied implicitly by use of conservative critical conditions for ambient barometric pressure, time of travel, and water temperature, and by the low probability that these critical conditions will occur at the same time. The potential for wind-induced degassing, which may occur on occasion but was not included in the TMDL, also provides a margin of safety. The TDG criterion itself provides a margin of safety due to its stringency as compared to site-specific effects documented by extensive site-specific research on TDG and aquatic life in the Snake River. Due to extensive data collection in the TMDL area, the margin of safety required for data uncertainty is small.

Seasonal Variation

Spills and associated high TDG levels, although most likely to occur in the spring and early summer, can potentially occur at any time. Therefore, TMDL load allocations apply year-round. Seasonal effects have been evaluated in the development of critical conditions, but seasonal variations appear to be small. The one exception is the water temperature increases in the pools; seasonal allocations have been applied to address this variability. The TMDL only applies for flows below the 7Q10 flood flows, which have been calculated for the TMDL area.

Monitoring Plan

Long-term compliance with load allocation will be monitored at the compliance location below the aerated zone with special studies in the tailrace of the dam, following structural modifications. Also, continuous monitoring will be used for long-term compliance by determining the statistical relationship between continuous monitors and conditions at the compliance location, and between the tailrace and downstream forebay monitor. Synoptic surveys may also be useful for establishing temperature increases in the pools, but will probably only be needed if changes in water temperature management are implemented. Monitoring of implementation and operational controls in the short term will use continuous monitoring at fixed monitoring station sites.

Implementation Plan

The Implementation Plan incorporates actions described and analyzed by the National Marine Fisheries Service in the Biological Opinion and by the U.S. Army Corps of Engineers in its

Dissolved Gas Abatement Study. Both short-term (Phase I) and long-term (Phase II) measures are described with specific TDG and spill reduction measures. Phase I is in effect until 2010, when Phase II begins and continues until 2020. The Implementation Plan has been developed in consultation with the National Marine Fisheries Service, so that TMDL implementation will be coordinated with requirements of the Endangered Species Act.

Reasonable Assurance

Structural work has already been carried out to reduce TDG at the four Lower Snake River dams. The Washington State Department of Ecology has regulatory authority over the four federal dam projects. However, Ecology is confident that the collaborative effort with the dam operators toward reducing gas will continue and be enhanced through this TMDL. The track record for Congressional funding for these projects is good, and there is reason to believe that further funding of projects will continue.

Public Participation

Extensive public involvement activities, organized by the inter-agency TMDL Coordination Team, have occurred under this TMDL for over a year. Activities have included websites, focus sheets, coordination meetings, stakeholder meetings, conference presentations, and public workshops. Public hearings were held in ________ (see *Summary of Public Involvement* section of this report).

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Introduction

State water quality standards establish criteria at levels that ensure the protection of the water's beneficial uses. Water that fails to meet water quality standards triggers a state action in Washington. The Washington State Department of Ecology is charged to assess, manage, and protect the beneficial uses of state waters.

A number of waterbodies fail to meet water quality standards. Washington is charged with returning waterbodies to standards. The requirement under the federal Clean Water Act for achieving this is known as a Total Maximum Daily Load (TMDL).

Washington has established criteria for total dissolved gas (TDG), which at high levels has deleterious effects on fish and other aquatic life. This document details a TMDL approach for TDG in the mainstem Snake River from the Idaho state line (just below the Clearwater River) to its mouth at the Columbia River (Figure 1). This report will describe the sources of TDG, explain why high TDG is a problem, and present a strategy for managing TDG so water quality standards will be met.

Compliance with Clean Water Act

The area for the Lower Snake River TDG TMDL begins at the Idaho border and falls entirely within the state of Washington. The state has adopted water quality standards for TDG to protect aquatic life. This entire reach of the river is out of compliance with the TDG water quality standard for the state of Washington, and is listed on its 1998 list of waterbodies failing to meet standards pursuant to Section 303(d) of the federal Clean Water Act. As a result of the standards exceedances and subsequent listings, this TMDL is being prepared by Washington State.

A TMDL determines the quantity (load) of a pollutant that can enter a waterbody and still meet water quality standards. This load is then allocated among the various sources. An implementation component (Summary Implementation Strategy or SIS) is included to identify actions that appropriate agencies and stakeholders will undertake to achieve the allocated loads.

The TMDL, as described in this document, must be submitted to the U.S. Environmental Protection Agency (EPA) for its approval. Washington operates under a Memorandum of Agreement (MOA) with EPA, which guides TMDL submittals. This document has been organized by the components described in the MOA.

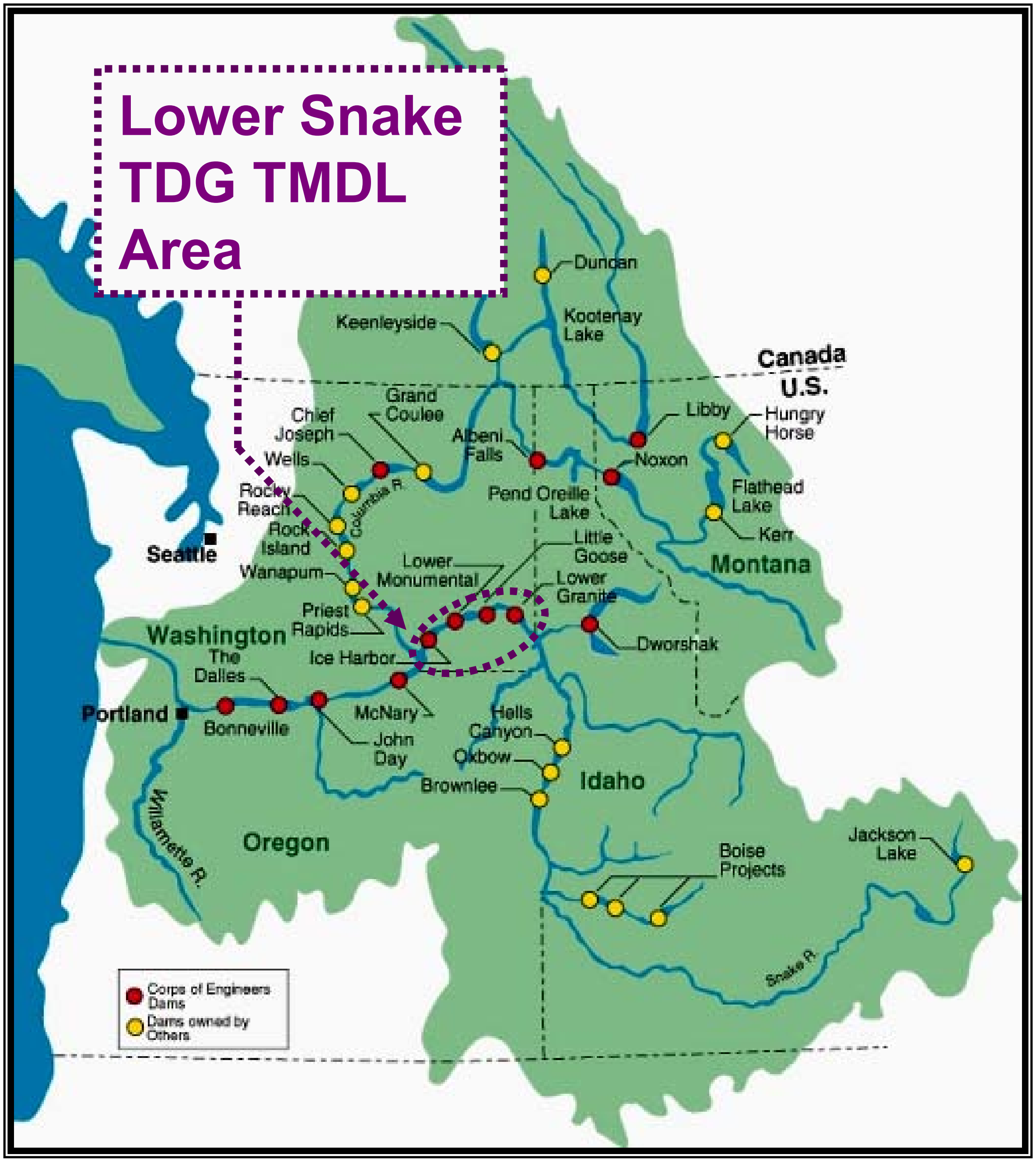

Figure 1. Map of Lower Snake TMDL Area.

Coordination with Endangered Species Act

A TMDL is a planning tool, not a rule of law or other stand-alone enforceable document. It does not take precedence over the federal Endangered Species Act, Indian Treaties, or federal hydropower system enabling legislation. It takes no action that would trigger a review under the National Environmental Policy Act or Washington State Environmental Policy Act. TMDLs may be used to condition exemptions, modifications, variances, permits, administrative orders, licenses, and certifications.

There is much overlap between this TMDL established pursuant to the federal Clean Water Act and other plans to protect salmonids listed as threatened or endangered under the Endangered Species Act, administered by the National Marine Fisheries Service (NMFS). It is therefore important that there is a clear understanding of the requirements of this TMDL relative to measures required by Biological Opinions issued in relation to the threatened and endangered species of the Snake and Columbia rivers.

The 2000 Federal Columbia River Power System (hydrosystem) Biological Opinion requires that the action agencies (U.S. Army Corps of Engineers, Bonneville Power Administration, and the U.S. Bureau of Reclamation) meet specific hydrosystem biological performance standards for both adult and juvenile salmon. The purpose of these standards is to help reverse the downward trend in listed salmon populations and therefore ensure viable salmon resources in the Columbia River Basin. The juvenile hydrosystem goals are one part of a three-tiered approach to assessing performance of implementation of the Reasonable and Prudent Alternative Section items presented in the Biological Opinion. These hydrosystem standards are combined with standards for harvest, habitat, and hatcheries and other life stage indicators to arrive at a population level standard.

The hydrosystem survival performance standards can be met by a combination of controlled spills, fish passage facilities to divert juvenile salmon from passing through the turbines, or juvenile transportation by truck or barge. Due to the current configuration of the hydroelectric projects along the Columbia and Snake rivers, NMFS sees spill as the available tool that is most effective for fish survival. However, these performance standards are not being met at the current implementation level of the spill program. Therefore, in the short-term, structural gas abatement solutions may result in higher spills rather than lower TDG levels. But as new, more effective fish passage facilities are completed and evaluated, their contribution to the attainment of hydrosystem performance standards will hopefully allow spill levels for fish passage and associated TDG levels to be reduced, but only so long as the performance standards are met.

Spills for fish passage under the Biological Opinion cause TDG supersaturation above the 110 percent criterion. The state water quality standards are meant to be sufficiently protective so as to prevent damage to beneficial use of the state waters. The effects of elevated dissolved gas on migrating juvenile and adult salmon due to voluntary spill have been monitored each year of spill program implementation. Based on five years of data from the biological monitoring program, the average incidence of gas bubble disease signs has been low, although the state-allowed maximum TDG due to spill was 120 percent in the tailrace and 115 percent in forebays. From 1995 to 1996, only 1.6 percent of all the juveniles sampled, nearly 200,000 fish, showed signs of disease (Schneider, 2001). These results suggest that, in weighing the benefit gained in increased salmon survival by spills for fish passage against the benefit to the beneficial use from strict adherence to the standard, it would be reasonable to find flexibility in application of the standards.

In summary, the provisions of both Acts must be met. Notwithstanding that, it is not the purpose of the Clean Water Act to usurp functions properly undertaken pursuant to the Endangered Species Act. On the contrary, the Endangered Species Act contains provisions that encourage EPA to consult with NMFS prior to approval of a TMDL that affects ESA-listed species to ensure the TMDL is consistent with species recovery goals. The 2000 Biological Opinion issued pursuant to the Endangered Species Act requires attainment of certain fish passage performance standards. One of the means of attaining these is through spilling water over hydroelectric dam spillways. This action, though, results in elevated TDG. Control of TDG is the purpose of this TMDL. The Clean Water Act does not envisage trade-offs of fish passage for TDG; it requires, rather, attainment of water quality standards. This is one of the significant challenges posed by this TMDL.

This TMDL must be written to reflect ultimate attainment of the TDG water quality standard. Fish passage requirements can be facilitated under an implementation plan, but the clear expectation of the Clean Water Act is that water quality standards will be attained in a limited amount of time. NMFS and EPA have been discussing how to meet biological performance standards under the Endangered Species Act at the same time as meeting the water quality standards of the Clean Water Act. However, the primary purpose of this TMDL must be to comply with the Clean Water Act, although finding a means of compliance with both laws is also a goal.

Applicable Criteria

The laws of the State of Washington apply to the Snake River from the Idaho border just below the mouth of the Clearwater River to its mouth at the Columbia River. All of these waters have been included on Washington's 1996 303(d) list, and have been identified as impaired or have been included on Washington's 1998 303(d) list. The segments covered by this TMDL are listed in Table 1, along with the Water Resource Inventory Area (WRIA) and Waterbody Identification (WBID) numbers.

A TMDL has been completed for the Lower Columbia River from the mouth of the Snake River to the Pacific Ocean, and another is planned for the Mid-Columbia River (Canada border to confluence with Snake River). This TMDL and the Mid Columbia TMDL at their downstream ends will address compliance with the Lower Columbia River TDG TMDL at its upstream end.

Table 1. Washington's Lower Snake River TDG Listed and Impaired Segments

Segment description	WRIA	WBID	1996 303(d) listings	1998 303(d) listings	1998 impaired but unlisted
Lower Snake from Palouse River to Mouth at Columbia River	33	WA-33-1010	**1**		
Lower Snake above and below Lower Monumental and Ice Harbor Dams		YB86JO		**7**	
Middle Snake from Clearwater River to Palouse River	35	WA-35-1010	**1**		
Middle Snake above and below Little Goose Dam		VB86JO		**2**	
Middle Snake below Lower Granite Dam		YB86JO		**1**	
Middle Snake above Lower Granite Dam		YB86JO			**1**
Totals			**2**	**10**	**4**

Washington's Water Quality Standards, Chapter 173-201A Washington Administrative Code (WAC), classify the reaches of the Columbia River covered by this TMDL as Class A. The following standards specifically apply to this TMDL:

WAC 173-201A-030:

Total dissolved gas shall not exceed 110 percent of saturation at any point of sample collection.

WAC 173-201A-060:

(4)(a) The water quality criteria herein established for total dissolved gas shall not apply when the stream flow exceeds the seven-day, ten-year frequency flood.

(b) The total dissolved gas criteria may be adjusted to aid fish passage over hydroelectric dams when consistent with a department approved gas abatement plan. This gas abatement plan must be accompanied by fisheries management and physical and biological monitoring plans. The elevated total dissolved gas levels are intended to allow increased fish passage without causing more harm to fish populations than caused by turbine fish passage. The specific allowances for total dissolved gas exceedances are listed as special conditions for sections of the Snake and Columbia rivers in WAC 173-201A-130 and as shown in the following exemption:

Special fish passage exemption for sections of the Snake and Columbia rivers: When spilling water at dams is necessary to aid fish passage, total dissolved gas must not exceed an average of one hundred fifteen percent as measured at Camas/Washougal below Bonneville dam or as measured in the forebays of the next downstream dams. Total dissolved gas must also not exceed an average of one hundred twenty percent as measured in the tailraces of each dam. These averages are based on the twelve highest hourly readings in any one day of total dissolved gas. In addition, there is a maximum total dissolved gas one hour average of one hundred twenty-five percent, relative to atmospheric pressure, during spillage for fish passage. These special conditions for total dissolved gas in the Snake and Columbia rivers are viewed as temporary and are to be reviewed by the year 2003.

(c) Nothing in these special conditions allows an impact to existing and characteristic uses.

The “ten-year, seven-day average flood” or “seven-day, ten-year frequency flood” are usually termed the “7Q10” flood flows.

The criteria in WAC section 173-201A-060 are sometimes termed the “waiver” TDG limits for fish passage. Since the Washington waiver limits are to be viewed as temporary, this TMDL cannot use the waiver limits as a compliance endpoint. TMDLs must by law ensure compliance with the existing permanent standards. There are separate processes to revise the water quality standards and establish new criteria. If the TDG standards are ever revised in a way that affects this TMDL, then the TMDL could be revisited and modified at that time.

The standards that authorize and describe the use of a mixing zone can be found in WAC 173-201A-100. Due to their length they will not be presented verbatim.

Background

Sources of Total Dissolved Gas

Total dissolved gas (TDG) levels can be increased above the water quality criteria by spilling water over spillways of dams. These are the major sources of elevated TDG in the Snake River mainstem. There are a variety of other ways that TDG may be elevated: passage of water through turbines, fishways, or locks; and natural processes such as natural waterfalls, low barometric pressure, high water temperatures, or high levels of biological productivity. However, the vast majority of the high TDG levels found in the Snake River are caused by spills from dams. Man-made sources other than spill are minor, and can be considered negligible. Natural processes may have a significant effect on TDG, and are addressed in setting load allocations.

Spill at dams occurs for several reasons:

1. To enhance downstream fish passage (to aid in the pursuit of Biological Opinion "Performance Standards" for fish survival under the Endangered Species Act).
2. To bypass water that exceeds the available hydraulic capacity of the powerhouse due to:
   - High river flows.
   - Lack of power market.
   - Maintenance, break-down, or other reasons.

The first type of spill is sometimes called "voluntary spill", while the second types are termed "involuntary spills". Figure 2 illustrates the typical configuration of a dam on the Lower Snake River. The reservoir impounded by the dam is often termed the "pool". The forebay is the area immediately above the dam. Most of the river passes the dam through the powerhouse or spillways (other than leakage and fish by-pass facilities). The stilling basin is the area below the spillway, usually lined with reinforced concrete, into which the discharge dissipates energy to avoid downstream channel degradation. The tailwater is the river below the dam, and the tailrace is the area immediately below the powerhouse and the stilling basin.

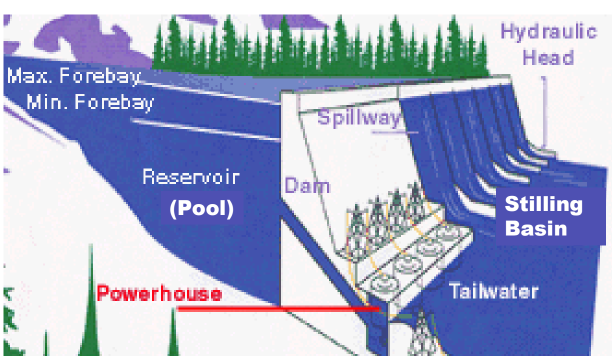

Figure 2. Typical Dam Configuration.

Spill for Fish Passage

Spill for purposes of fish passage involves water deliberately released over dam spillways, rather than being discharged through turbines or fish bypass facilities. The intent is to increase juvenile passage number and survival by redirecting fish to the spill, which has lower levels of mortality than turbine passage. For example, Schoeneman et al (1961) found that mortality in Chinook juveniles spilled over McNary Dam (Columbia River) and Big Cliff Dam (Santiam River) was less than two percent. Subsequent studies confirmed this estimate, and research is ongoing. The requirement for spring and summer spills to pass juvenile salmon was included in the 1995 and 2000 Biological Opinions for the Columbia and Snake River dam operations. Washington's approach to conform with the Biological Opinion was to adopt a rule revision specifying the TDG criteria for fish passage spill (see above).

Involuntary Spill

Like spills for fish passage, involuntary spill involves water being discharged over dam spillways. The causes and intended consequences, though, are different. As its name suggests, there is no alternative to an "involuntary" spill once one is required. (However, sometimes involuntary spill could possibly have been avoided by better planning.) At times of very high river flows, the quantity of water exceeds the capacity of a dam to either temporarily store the water upstream of the dam or pass the water through its turbines. In these circumstances, water is released over the spillway, because there is nowhere else for it to go.

The Lower Snake River Dams have very little storage capacity relative to the quantity of spring runoff. At times of rapid runoff, the dams cannot constrain the quantity of water, and it is spilled with attendant high TDG levels. Often dissolved gas levels from involuntary spill exceed those experienced during periods of spill for fish. However, high river flows under these circumstances are often in excess of the 7Q10 high flow, in which case the TDG standard would not apply.

Involuntary spill as a result of lack of power market is a variant of the above. In this scenario, the power marketing authority cannot sell any more power, and even though turbines are available, water is released over the spillway because there is nowhere for electricity generated to go. Running water through the turbines with no load increases wear and tear with attendant higher maintenance costs, and also may reduce fish survival. Lack of power load demand can occur at times of both high and low flows (e.g., in the spring or fall when power demands are low both in California and the Pacific Northwest). Also releases from upstream storage dams during high load times (morning and evening) can result in high flows at downstream dams during low load times (middle of the night), causing an involuntary spill.

Involuntary spill can also occur at low flows when powerhouses are taken off-line for maintenance, breakdown, or other needs. Maintenance is usually scheduled to prevent a spill, by doing maintenance on one or two generating units at a time during low power demand periods. Nonetheless, releases from upstream dams can complicate management of spills during powerhouse maintenance. Also, unscheduled maintenance and repairs sometimes occur, which may require a powerhouse shut-down and involuntary spill.

In general, involuntary spill conditions at the "run of the river" dams may result from reservoir control and power marketing decisions made by the federal project operators having storage capacity upstream. Improved accuracy in water forecasting could help avoid understating or overstating available water supply, which could cause the federal project operators to spill water because they left too little or too much room in the reservoirs. Additionally, a water management plan could also identify uncoordinated releases and manage daily fluctuations in river flows. These events often result in isolated involuntary spill events, because reservoir elevation must be maintained within limits at run of the river projects.

Water Quality and Resource Impairments

TDG Generation from Spills

Spills for fish passage typically occur during the spring and summer months. During periods of fish spills, deviations of ambient conditions from the water quality standard are frequent but usually small. This is because spill quantities are managed to meet the waiver levels for fish passage through Washington's Special Conditions (described above), which allow TDG levels to rise to 120 percent of saturation relative to atmospheric pressure in the tailrace of the dam that is spilling, and 115 percent in the forebay of the next dam downstream.

The excursions beyond this level usually have been no more than one or two percent above the waiver levels, due mainly to the many sources of TDG variability. Generally, the fishery management agencies have sought spill quantities that remain right at the TDG variance limit at the fixed monitoring station sites in order to maximize the juvenile passage and survival benefits. Any small change in conditions that influence TDG, such as change in barometric pressure, water temperature, degassing rates, incoming gas, total river flow, or tailwater elevation will cause an exceedance when operated this way. Also, these levels do not meet the 110 percent criterion of Washington State.

Nonetheless, the fisheries agencies and the Corps of Engineers are quick to note the exceedances and make necessary corrections to bring the levels into compliance. Also, TDG levels within the range of these small excursions above the waiver levels have been incorporated into the fish recovery spill program. The program includes biological monitoring for gas bubble trauma, which has consistently shown minimal levels of symptoms in downstream migrants.

Involuntary spills can occur at any time. Involuntary spills caused by river flows above powerhouse capacity are most likely to occur from late fall to early summer, depending on rainfall or snowmelt in the tributary watersheds. However, high flows could also occur due to releases from upstream dams with significant storage, such as Brownlee or Dworshak dams. Involuntary spill due to low power demand is most likely in the spring, although this is also dependent on regional power management by the Bonneville Power Administration. Loss of powerhouse capacity to maintenance or repair is usually scheduled so that no more than one or two turbines are out at any given time, but an emergency powerhouse shutdown and spill could occur at any time as the result of a fire or other disaster.

At times of involuntary spill, exceedances above the standard can rise dramatically, peaking above 130 percent of saturation, and even 140 percent. Absolute TDG pressures at these levels, which usually only occur in shallow waters, can be lethal to fish. Usually fish are protected from fatal pressures in deeper waters by compensation from hydrostatic pressures, which reduces absolute TDG levels.

For all spills, the highest TDG levels, and therefore the area most likely to exceed standards, are in the stilling basin directly below the spillway. In this area, the "aerated zone", the plunging and air entrainment of the spill generates high levels of TDG, but then quickly degasses while the water remains turbulent and full of bubbles. As this water moves from the stilling basin into the tailrace, the bubbles rise and dissipate, degassing slows, and the TDG levels stabilize.

In the pools, if TDG pressures are not at 100%, gas in the water will be seeking equilibrium with the air. High TDG levels will produce degassing, but the loss rate is controlled conditions such as the depth of water, surface area, and surface mixing. Degassing rates increase as the wind speed rises, or as the river gets wider, shallower, or more turbulent (such as in a rapid or cascades).

Snake River reservoirs are generally deep and slow, and in the absence of wind degassing rates are very low. Under these conditions TDG concentrations remain essentially constant, but the percent saturation of TDG can increase if the water temperature increases or barometric pressure drops (Figure 3). Also, primary productivity (periods of algal growth) can increase dissolved oxygen levels, which results in a higher TDG percent saturation. However, because oxygen is metabolized by the aquatic life its physical effects are minor compared to nitrogen, and therefore can also be considered *de minimus.*

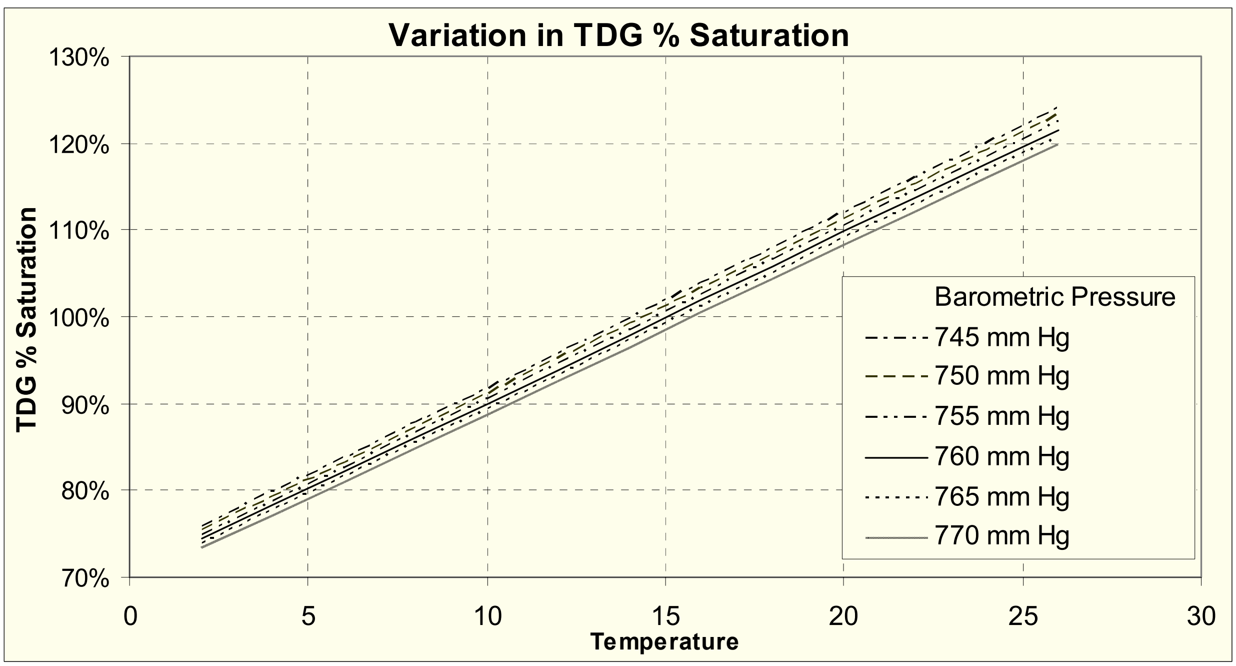

Figure 3. Variation in TDG Percent Saturation with Temperature and Barometric Pressure at Constant Concentration.

Due to the hydraulic properties of the spill, a proportion of the powerhouse flow entrains with the spill and is aerated as if it were part of the spill. (This amount may be negligible where physical structures separate powerhouse from spillway flows, such as islands at Bonneville Dam, but no such structures currently exist on the Lower Snake River.) The rest of the powerhouse flow mixes with the spillway flows at varying rates, sometimes quite slowly, as the river moves downstream from the dam. Powerhouse TDG levels are typically identical with forebay TDG levels – very little gas exchange occurs as water passes through the powerhouse. Therefore, if the forebay TDG levels are lower than levels below the spillway, the powerhouse flows that mix slowly and farther downstream will reduce the TDG levels in the spillway waters by dilution.

TDG Impacts on Aquatic Life

Fish and other aquatic life inhabiting water supersaturated with TDG may tend to display signs of difficulty, especially if higher dissolved gas pressure gradients occur. Gas bubbles form only when the TDG pressure is greater than the sum of the compensating pressures. Compensating pressures include water (hydrostatic) and barometric pressure. For organisms, tissue or blood pressure may add to the compensating pressures. Gas bubble development in aquatic organisms is then a result of excessive uncompensated gas pressure. The primary actions which will enhance the likelihood of bubbles forming in the fish are (1) continued exposure to the highly saturated water, (2) rising higher in the water column bringing about a higher pressure gradient (decreased hydrostatic pressure), (3) decreases in barometric pressure, and (4) increasing water temperature.

The damage caused by release of gas bubbles in the affected organism is termed gas bubble trauma or gas bubble disease. There is a wide body of research on this condition. Effects of gas bubble trauma include emphysema, circulatory emboli, tissue necrosis, and hemorrhages in brain, muscle, gonads, and eyes (Weitkamp and Katz 1980). Nebeker et al. (1976) found that death in adults was due to massive blockages of blood flow from gas emboli in the heart, gills, and other capillary beds. Investigators in the 1970s reported many and varied lesions in fish exposed in the 115%-to-120% TDG range in shallow water. At higher gas exposures, e.g.,120% to 130% TDG, death frequently ensued before gas bubble trauma signs appeared (Bouck et al. 1976). External signs of gas bubble trauma, e.g., blisters forming in the mouth and fins of fish exposed to chronic high gas, often disappeared rapidly after death. The signs were largely gone within 24 hours (Coutant and Genoway 1968).

Water quality standards for TDG were set at 110 percent, the threshold for chronic effects found in the literature. The severity of gas bubble trauma increases as the absolute TDG level increases, until at higher levels lethality can occur swiftly. However, there are a number of factors that affect a particular organism’s response to high TDG levels. Different species respond to changing TDG differently, and the response also varies by life stage. Juvenile salmonids appear to be relatively resilient compared to adults or to non-salmonids.

The duration of exposure to high TDG appears to have an impact on the severity of gas bubble trauma symptoms. Although the standards are not specific on this issue, defining a duration of exposure to be applied to the criteria is appropriate. The waiver limits developed for fish passage provide two levels: a one hour maximum, and the average of the twelve highest hourly readings in any 24-hour period. Based on the 110 percent criteria representing chronic impacts, use of the longer averaging period is appropriate.

Extensive research has been conducted on the effects of TDG on anadromous fish in the Columbia and Snake Rivers. It is beyond the scope of this TMDL to review that literature. The Clean Water Act requires compliance with existing standards, although existing research can be used to aid in interpretation of those standards. A review of the standards to look at adoption of different criteria, duration, frequency, and spatial application, if appropriate, would occur through a completely separate process. If new standards were adopted, then the TMDL could be reviewed and possibly revised.

It is possible that TDG became elevated under historical natural conditions in the Columbia and Snake River, such as below Celilo Falls. However, elevated TDG may also have dissipated quickly as it passed over shallows and rapids. Conditions different from natural conditions exist at the Columbia and Snake River dams that create high TDG levels. These conditions include the height of the dams, the shape of the spillways, and the presence of the long deep pools below the dams. Allowing a point of compliance below the aerated portion of the tailrace can be considered to reflect gas generation patterns in a natural system.

Monitoring of TDG

Routine monitoring of instream TDG levels occur at fixed monitoring station (FMS) sites above and below each dam. The tailwater FMS sites in some cases may be a mile or two downstream of the dam. The FMS sites have been the primary point of compliance and assessment of TDG levels, especially for compliance with waiver limits during fish passage spills. The locations have been chosen for a variety of reasons, a primary one being the logistics and feasibility of long-term monitoring. However, studies suggest that data from some of these sites may not be consistently representative of river conditions. The FMS sites will continue to be the primary location for determining compliance with waiver limits used for fish passage management. For the purposes of TMDL compliance, TMDL requirements do not need to drive FMS siting issues.

The interagency Water Quality Team manages issues regarding the fish passage program and FMS. The Water Quality Team is jointly chaired by NMFS and EPA and is charged with providing technical advice and guidance on temperature and total dissolved gas water quality in the context of the NMFS 2000 Biological Opinion relating to the Columbia River Hydropower System. A subgroup of that team has been addressing concerns with the FMS sites, and the appropriateness of the current FMS locations has been the subject of vigorous debate between the resource agencies and U.S. Army Corps of Engineers within the subgroup. The subgroup has concluded that the "representativeness" of FMS data is a very difficult characteristic to define. The TDG measurements at a given location in the river are influenced significantly by environmental factors such as water temperature, biological productivity, barometric pressure, and wind, as well as the spill. The Water Quality Team will continue to study and discuss these issues in order to achieve a mutually satisfactory monitoring end product.

To gain additional knowledge of TDG conditions in the river, the Corps has conducted a number of detailed special studies of TDG levels below the dams (e.g., Schneider and Wilhelms, 1996, 1997, 1998a, 1998b, and 1998c). These studies have shown that TDG levels measured at the FMS sites are usually lower than levels longitudinally upstream towards the spillway, may be lower than levels laterally across the river if powerhouse flows are not fully mixed, and in some conditions may be lower than levels longitudinally downstream.

Technical Analysis

Analysis of TDG generation processes

Introduction

The discussion that follows is taken (sometimes verbatim) from the Dissolved Gas Abatement Study (DGAS) conducted by the U.S. Army Corps of Engineers, and in particular from Appendix G: "Spillway Discharge Production of Total Dissolved Gas Pressure" (USACE, 2001a).

The material in this section provides a general overview of TDG generation processes at the Lower Snake River dams. Specific details may change over time as structural changes are made to these projects. These processes provide the basis for the determination of loading capacity.

The TDG exchange associated with spillway operation at a dam is a process that couples both the hydrodynamic and mass exchange processes. The hydrodynamics are shaped by the structural characteristics of spillway, stilling basin, and tailrace channel as well as the operating conditions that define the spill pattern, turbine usage, and tailwater stage. The hydrodynamic conditions are influenced to a much smaller extent by the presence of entrained bubbles.

The air entrainment will influence the density of the two-phase flow and impose a vertical momentum component associated with the buoyancy in the entrained air. The entrained air content can result in a bulking of the tailwater elevation and influence the local pressure field. The transfer of atmospheric gasses occurs at the air-water interface, which is composed of the surface area of entrained air at the water surface. The exchange of atmospheric gases is greatly accelerated when entrained air is exposed to elevated pressures because of the higher saturation concentrations. The pressure time history of entrained air will, therefore, be critical in determining the exchange of atmospheric gases during spill.

The volume, bubble size, and flow path of entrained air will be dependent on the hydrodynamic conditions associated with project releases. The bubble size has been found to be a function of the velocity fluctuations and turbulent eddy length. The bubble size can also be influenced by the coalescence of bubbles during high air concentration conditions. The volume of air entrained is a function of the interaction of the spillway jet with the tailwater. The entrained bubble flow path will be dependent upon the development of the spillway jet in the stilling basin and associated secondary circulation patterns. The turbulence characteristics are important to the vertical distribution of bubbles and the determination of entrainment and de-entrainment rates.

Physical Processes

The exchange of TDG is considered to be a first order process where the rate of change of atmospheric gases is directly proportional (linear relationship) to the ambient concentration. The driving force in the transfer process is the difference between the TDG concentration in the water and the saturation concentration with the air. The saturation concentration in bubbly flow will be greater than that generated for non-bubbly flow where the saturation concentration is determined at the air-water interface. The flux of atmospheric gasses across the air-water interface is typically described by Equation 1.

$$J = K_l (C_s - C) \qquad \text{Equation 1}$$

Where:

J	=	gas flux (mass per surface area per time)
K_l	=	the composite liquid film coefficient
C_s	=	the saturation concentration (mass per volume)
C	=	the ambient concentration in water (mass per volume)

The rate of change of concentration in a well-mixed control volume, $\frac{dC}{dt}$, can be estimated by multiplying the mass flux by the surface area and dividing by the volume over which transfer occurs as shown by Equation 2:

$$\frac{dC}{dt} = K_l \frac{A}{V} (C_s - C) \qquad \text{Equation 2}$$

Where:

A	=	the surface area associated with the control volume
V	=	the volume of the waterbody over which transfer occurs

This relationship shows the general dependencies of the mass transfer process. In cases where large volumes of air are entrained, the time rate of change of TDG concentrations can be quite large, as the ratio of surface area to volume becomes large. The entrainment of air will also result in a significant increase in the saturation concentration of atmospheric gases, thereby increasing the driving potential over which mass transfer takes place. Outside of the region of aerated flow during transport through the pools, the contact area is limited to the water surface and the ratio of the surface area to the water volume becomes small, thereby limiting the change in TDG concentration. The turbulent mixing will influence the surface renewal rate and hence the magnitude of the exchange coefficient K_l.

Equation 2 can be integrated, provided the exchange coefficient, area, and volume are held constant over the time of flow. The initial TDG concentration at time=0 is defined as C_i and the final TDG concentration time=t is defined as C_f shown in Equation 3. The resultant concentration C_f exponentially approaches the saturation concentration for conditions where the term $K_l \frac{A}{V}$ is large. The final concentration becomes independent of the initial concentration under these conditions.

$$C_f = C_s(l - e^{-K_l \frac{A}{V} t}) + C_i e^{-K_l \frac{A}{V} t} \quad \text{Equation 3}$$

Modeling TDG Transfer

The TDG exchange process involves the coupled interaction of project hydrodynamics and mass transfer between the atmosphere and the water column. Mechanistic models of TDG transfer must simulate the two-phase (liquid and gas phases) flow conditions that govern the exchange process. Several mechanistic models have been developed to simulate the TDG exchange in spillway flows.

Orlins and Gulliver (2000) solved the advection-diffusion equation for spillway flows at Wanapum Dam for different spillway deflector designs. Physical model data were used to develop the hydraulic descriptions of the flow conditions throughout the stilling basin and tailrace channel. The model results were also compared to observations of TDG pressure collected during field studies of the existing conditions.

A second model developed by Urban et al. (2000), used the same mass transport relationships together with the hydraulic descriptions associated with plunging jets. This approach does not require the specific hydraulic information to be derived from a physical model, but it can be applied to any hydraulic structure that has plunging jet flow. This model accounted for the TDG exchange occurring across the bubble-water interface and the water surface. This model was calibrated to observations of TDG exchange at The Dalles Lock and Dam (The Dalles) and was developed as part of DGAS. This model successfully simulated the absorption and desorption exchange caused by the highly aerated flow during spillway operations.

As a part of its DGAS study, the Corps decided to use empirically derived equations of TDG exchange, based on the recognition that data were not available to support mechanistic models of the mass exchange process at all the projects in the Columbia/Snake River system. The greatest unknowns associated with the development of a mechanistic model of highly aerated flow conditions in a stilling basin revolve around the entrainment of air and subsequent transport of the bubbles. The surface area responsible for mass transfer will require estimates of the total volume and bubble size distribution of entrained air. In addition, the roughened water surface is thought to contribute to the net exchange of atmospheric gasses. The pressure time history of entrained air would also need to be accounted for to determine the driving potential for TDG mass exchange.

A description of the highly complex and turbulent three-dimensional flow patterns in the stilling basin and adjoining tailrace channel would need to be defined for a wide range of operating conditions. The influence of turbulence on both the mass exchange coefficients and redistribution of buoyant air bubbles would also need to be quantified throughout a large channel reach and for a wide range of operating conditions.

The flow conditions generated by spillway flow deflectors have been found to be sensitive to both the unit spillway discharge and submergence of the flow deflector. The presence of flow deflectors has significantly changed the rate of energy dissipation in the stilling basin and promotes the lateral entrainment of flow. These entrainment flows are often derived from powerhouse releases, which reduce the available volume of water for dilution of spillway releases.

TDG Exchange Formulation

The accumulated knowledge generated through observations of flow conditions during spill at Columbia/Snake River projects and in-scale physical models at the Waterways Experiment Station in Vicksburg, MS, along with mass exchange data collected during site-specific near-field TDG exchange studies and from the fixed monitoring stations, has led to the development of a model for TDG exchange at dams throughout the Columbia/Snake river system for the federal hydropower projects. The general framework is based upon the observation that TDG exchange is an equilibrium process that is associated with highly aerated flow conditions that develop below the spillway. It recognizes that flow passing through the powerhouse is not generally exposed to entrained air under pressure and, therefore, does not experience a significant change in TDG pressure. It also recognizes that powerhouse releases can directly interact with the aerated flow conditions below the spillway and experience similar changes in TDG pressure that are found in spill.

The large volume of air entrained into spillway releases initiates the TDG exchange in spill. This entrained air is exposed to elevated total pressures and the resulting elevated saturation concentrations. The exposure of the bubble to elevated saturation concentrations greatly accelerates the mass exchange between the bubble and water. The amount and trajectory of entrained air is greatly influenced by the structural configuration of the spillway and the energy associated with a given spill.

The presence of spillway flow deflectors directs spill throughout the upper portion of the stilling basin, thereby preventing the plunging of flow and transport of bubbles throughout the depth of the stilling basin. Spillway flow deflectors also greatly change the rate of energy dissipation in the stilling basin, transferring greater energy and entrained air into the receiving tailrace channel.

Generally, spill water experiences a rapid absorption of TDG pressure throughout the stilling basin region where the air content, depth of flow, flow velocity, and turbulence intensity are generally high. As the spillway flows move out into the tailrace channel, the net mass transfer reverses and component gases are stripped from the water column as entrained air rises and is vented back to the atmosphere. The region of rapid mass exchange is limited to the highly aerated flow conditions within 1,000 feet of the spillway.

In general, downstream of the aerated flow conditions, the major changes to the TDG pressures occur primarily through the redistribution of TDG pressures through transport and mixing processes. The in-pool equilibrium process established at the water surface is chiefly responsible for changes to the total TDG loading in the river.

One of the more important observations regarding TDG exchange in spillway flow is the high rate of mass exchange that occurs below a spillway. The resultant TDG pressure generated during a spill is almost entirely determined by physical conditions that develop below the spillway and is effectively independent from the initial TDG content of this water in the forebay. The TDG exchange in spill is not a cumulative process where higher forebay TDG pressures will generate yet higher TDG pressures downstream in spillway flow. The TDG exchange in spill is an equilibrium process where the time history of entrained air below the spillway will determine the resultant TDG pressure exiting the vicinity of the dam.

One consequence of this observation is that spilling water can result in a net reduction in the TDG loading in a system if forebay levels are above a certain value. This was a common occurrence at The Dalles during the high-flow periods during 1997 where the forebay TDG exceeded 130 percent saturation. A second consequence of the rapid rate of TDG exchange in spill flow is that the influence from upstream projects on TDG loading will be passed downstream only through powerhouse releases. If project operations call for spilling a high percentage of the total river flow, the contribution of TDG loading generated from upstream projects will be greatly diminished below this project.

Given the conceptual framework for TDG exchange described above, the average TDG pressures generated from the operation of a dam can be represented by the mass conservation statement using TDG pressure shown in Equation 4:

$$P_{avg} = \frac{(Q_{sp} + Q_e)P_{sp} + (Q_{ph} - Q_e)P_{ph}}{Q_{sp} + Q_{ph}} \qquad \text{Equation 4}$$

Where:

Q_{sp}	=	Spillway discharge [thousands of cubic feet per second (kcfs)]
Q_{ph}	=	Powerhouse discharge (kcfs)
Q_e	=	Entrainment of powerhouse discharge in aerated spill (kcfs)
Q_{se}	=	$Q_{sp} + Q_e$
	=	Effective spillway discharge (kcfs)
Q_{tot}	=	$Q_{sp} + Q_{ph}$
	=	Total river flow (kcfs)
P_{ph}	=	TDG pressure releases from the powerhouse [mm Hg]
P_{sp}	=	TDG pressure associated with spillway flows (mm Hg)
P_{avg}	=	Average TDG pressure associated with all project flows (mm Hg)

This conservation statement assumes the water temperature of powerhouse and spillway flows are similar, and that the heat exchange during passage through the dam and aerated flow region is minimal. Some projects have other water passage routes besides the powerhouse and spillway, such as fish ladders, lock exchange, juvenile bypass systems, and other miscellaneous sources.

These sources of water have generally been lumped into powerhouse flows and are not accounted for separately.

Equation 4 contains three unknowns: Q_e = powerhouse entrainment discharge, $P_{sp} = TDG$ pressure associated with spillway flows, and $P_{ph} = TDG$ pressure associated with powerhouse releases. The TDG pressure associated with the powerhouse release is generally assumed to be equivalent to the TDG pressure observed in the forebay. Numerous data sets support the conclusion that turbine passage does not change the TDG content in powerhouse releases. All of the near-field TDG exchange studies have deployed TDG instruments in the forebay of a project and directly below the powerhouse in the water recently discharged through the turbines. An example of this type of data is shown in Figure 4 during the 1998 post-deflector John Day Lock and Dam (John Day) TDG exchange study (Schneider and Wilhelms, 1999a).

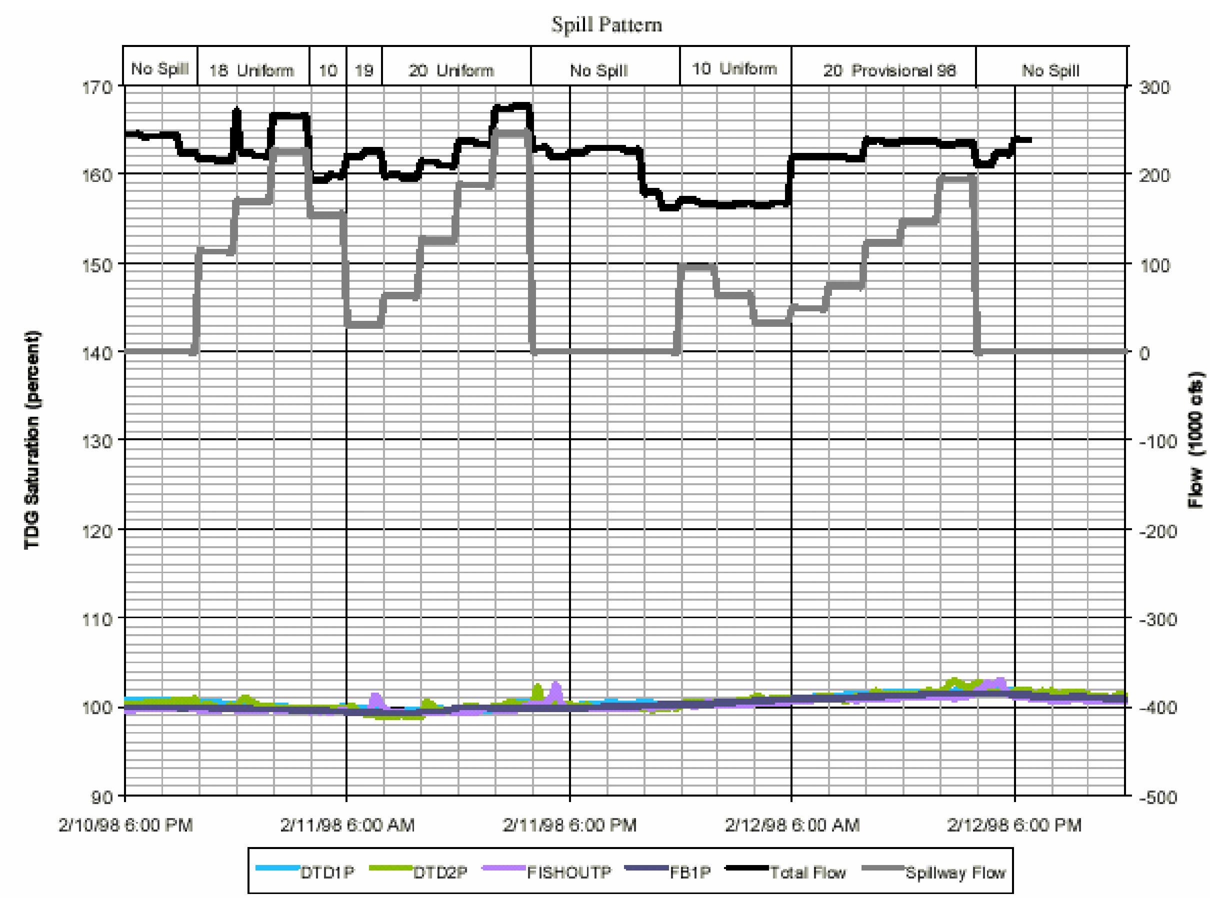

Figure 4. TDS Saturation in the Forebay and Below the Powerhouse Draft Tube Deck of John Day Dam, February 1998.

The TDG instruments were deployed in the forebay of John Day (station FB1P) and in the tailwater below powerhouse draft tube deck (station DTD1P and DTD2P), near the fish outfall (FISHOUTP). The TDG pressure was logged on a 15-minute interval at each of these stations throughout the testing period. All four stations recorded the same TDG saturations throughout the testing period, even during operating events calling for spilling nearly the entire river on February 11 and 12. The TDG pressure from the forebay and tailwater fixed monitoring stations should also be similar during periods of no spill, provided that these stations are sampling water with similar water temperatures. In cases where a turbine aspirates air or air is injected into a turbine to smooth out operation, the above assumption will not hold.

Spillway TDG Exchange

The TDG exchange associated with spillway flows has been found to be governed by the geometry of the spillway (standard or modified with flow deflector), unit spillway discharge, and depth of the tailrace channel. The independent variable used in determining the exchange of TDG pressure in spillway releases is the delta TDG pressure (ΔP) defined by the difference between the TDG pressure (P_{tdg}) and the local barometric pressure (P_{bar}) as listed in Equation 5. The selection of TDG pressure as expressed as the excess pressure above atmospheric pressure accounts for the variation in the barometric pressure as a component of the total pressure.

$$\Delta P = P_{tdg} - P_{bar} \qquad \text{Equation 5}$$

Restating the exchange of atmospheric gases in terms of mass concentrations introduces a second variable (water temperature) into the calculation. The added errors in calculating the TDG concentration as a function of temperature and TDG pressure were the main reasons for using pressure as the independent variable. The TDG concentration would also vary seasonally with the change in water temperature.

The TDG pressure is often summarized in terms of the percent saturation or supersaturation. The TDG saturation (S_{tdg}) is determined by normalizing the TDG pressure by the local barometric pressure as expressed as a percentage. The delta pressure has always been found to be a positive value when spillway flows are sampled. The TDG saturation (S_{tdg}) is determined by Equation 6.

$$S_{tdg} = \frac{P_{tdg}}{P_{bar}} * 100 = \frac{(P_{bar} + \Delta P)}{P_{bar}} * 100 \qquad \text{Equation 6}$$

Unit Spillway Discharge

The TDG exchange associated with spillway flows has been found to be a function of unit spillway discharge (q_s) and the tailrace channel depth (D_{tw}). The unit spillway discharge is a surrogate measure for the velocity, momentum, and exposure time of aerated flow associated with spillway discharge. The higher the unit spillway discharge, the greater the TDG exchange during spillway flows. An example of the dependency between the change in TDG pressure and unit spillway discharge is shown in Figure 5 at Ice Harbor Lock and Dam (Ice Harbor).

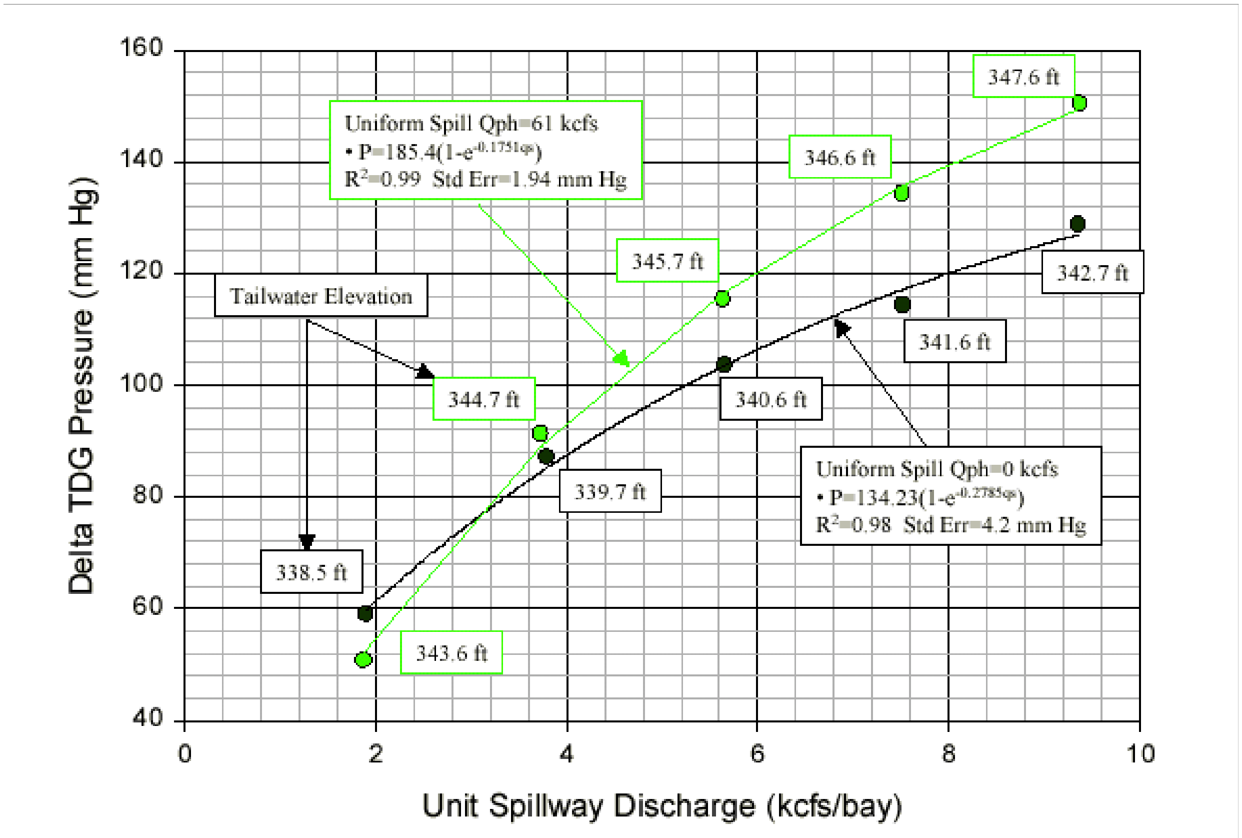

Figure 5. TDG Pressure (Delta P) as a Function of Unit Spillway Discharge and Tailwater Elevation at Ice Harbor Dam, March 1998.

This figure shows two sets of tests involving a uniform spill pattern over eight bays with flow deflectors. The two sets of tests were distinguished only by the presence of powerhouse releases. In both cases, the resultant spill TDG pressure was found to be an exponential function of the unit spillway discharge. The determination of a single representative unit discharge becomes problematic in the face of a non-uniform spill pattern. The flow-weighted specific discharge was found to be a better determinant of spillway TDG production in cases where the spill pattern is highly non-uniform. The flow-weighted unit discharge places greater weight on bays with the higher discharges. The following Equation 7 describes the determination of the specific discharge used in the estimation of TDG exchange relationships:

$$q_s = \frac{\sum_{i=1}^{nb} Q_i^2}{\sum_{i=1}^{nb} Q_i} \qquad \text{Equation 7}$$

Where:

q_s	=	Specific discharge (flow-weighted unit discharge)
Qi	=	Flow for spill bay i (for nb number of bays)

Depth of Flow

The large amount of energy associated with spillway releases has the capacity to transport entrained air throughout the water column. In many cases, the depth of flow is the limiting property in determining the extent of TDG exchange below a spillway. An example of the influence of the depth of flow on TDG exchange is shown in Figure 5 at Ice Harbor. The only difference between the two sets of data in this figure was the presence of powerhouse flow. The events with powerhouse flow resulted in higher TDG pressure than comparable spill events without powerhouse releases at higher spillway flows. The observed tailwater elevation is also listed in Figure 5 for each test event. The tailwater elevation was about five feet higher during the events corresponding with powerhouse operation.

The depth of flow in the tailrace channel was hypothesized to be more relevant to the exchange of TDG pressure than the depth of flow in the stilling basin because of the influence of the flow deflectors and resultant surface jet, and the high rate of mass exchange observed below the stilling basin. The average depth of flow downstream of the stilling basin was represented as the difference between the tailwater elevation as measured at the powerhouse tailwater gauge and the average tailrace channel elevation within 300 feet of the stilling basin. The tailrace channel reach within 300 feet of the stilling basin was selected because most of the TDG exchange (degassing) occurs in this region. A summary of project features at the time of the Corps DGAS study are listed in Table 2, including stilling basin elevation, deflector elevation, and tailrace channel elevation.

Table 2. Snake River Project Features (April 2001)

Project	Spillway Crest Elev. (ft)	Number Spillways: Deflectors		Deflector Elevation (ft)	Stilling Basin Elev. (ft)	Tail-water Channel Elev. (ft)	Normal Tail-water Pool (ft)	Normal Tail-water Depth (ft)
		w/	w/out					
Ice Harbor	391	10	0	338	304	327	344	17
Lower Monumental	483	6 (8) [1]	2 (0) [1]	434	392	400	441	41
Little Goose	581	6	2	532	466	500	539	39
Lower Granite	681	8	0	630	580	604	635	39

Source: U.S. Army Corps of Engineers DGAS Study, Appendix G, p. G-8 (USACE, 2001a)
[1]Additional deflectors are under construction to be completed by March 2003.

The functional form of the relationship between the change in TDG pressure change and the prominent dependent variables unit spillway discharge and tailrace channel depth of flow, takes the same form as the exponential formulation shown in Equation 3. The delta TDG pressure was found to be a function of the product of the depth of flow and the exponential function of unit spillway discharge as shown in Equation 8.

$$\Delta P = C_1 D_{tw}(1 - e^{-c_2 q_s}) + C_3 \qquad \text{Equation 8}$$

The coefficients C_1, C_2, and C_3 were determined from nonlinear regression analyses. The product of C_1 and the tailwater depth (D_{tw}) represents the effective saturation pressure in Equation 3 while the product of C_2 and the unit spillway discharge (q_s) reflects the combined contribution from the mass exchange coefficient, ratio of surface area to control volume, and time of exposure.

A second formulation used in this study relating the delta TDG pressure and independent variable involves a power series as shown in Equation 9. This equation can also result in a linear dependency between the delta TDG pressure and either tailwater depth or unit spillway discharge. A linear dependency in the tailwater depth occurs when C_2=1 and C_3=0. A linear dependency between TDG pressure and unit spillway discharge occurs when C_2=0 and C_3=1.

$$\Delta P = C_1 D_{tw}^{C_2} q_s^{C_3} + C_4 \qquad \text{Equation 9}$$

Entrainment of Powerhouse Flow

The interaction of powerhouse flows and the highly aerated spillway releases can be considerable at many of the projects. Observations of the flow conditions downstream of projects where the powerhouse is adjacent to the spillway often indicate a strong lateral current directed toward the spillway.

The clearest example of the influence of the entrainment of powerhouse flow on TDG exchange was documented during the near-field TDG exchange study at Little Goose. The study at Little Goose was conducted during February 1998 when the ambient TDG saturation in the Snake River ranged from 101 to 103 percent. The test plan called for adult and juvenile fish passage spill of up to 60 kcfs with the powerhouse discharging either 60 kcfs or not operating. The cross-sectional average TDG pressure in the Snake River below Little Goose was determined from seven separate sampling stations located across the river from the tailwater FMS. The project operations and resultant TDG saturation are summarized in Figure 6 where the observations from the forebay and tailwater fixed monitoring stations are shown as LGS and LGSW respectively, the cross-sectional average TDG saturation at the tailwater FMS is labeled $T5_{avg}$, and the flow-weighted average TDG saturation assuming no entrainment of powerhouse flow is labeled FWA (flow-weighted average).

The TDG saturation estimated by assuming that powerhouse releases were available to dilute spillway flows during this test (FWA) were significantly less than estimates derived from averaging information from the seven sampling stations at the tailwater fixed monitoring station ($T5_{avg}$). This study demonstrated that nearly all of the powerhouse flows from Little Goose were entrained and acquired TDG pressures similar to those in spillway flows during this study.

The circulation patterns below the dam during the test clearly supported the TDG data indicating high rates of entrainment of powerhouse flows into the stilling basin.

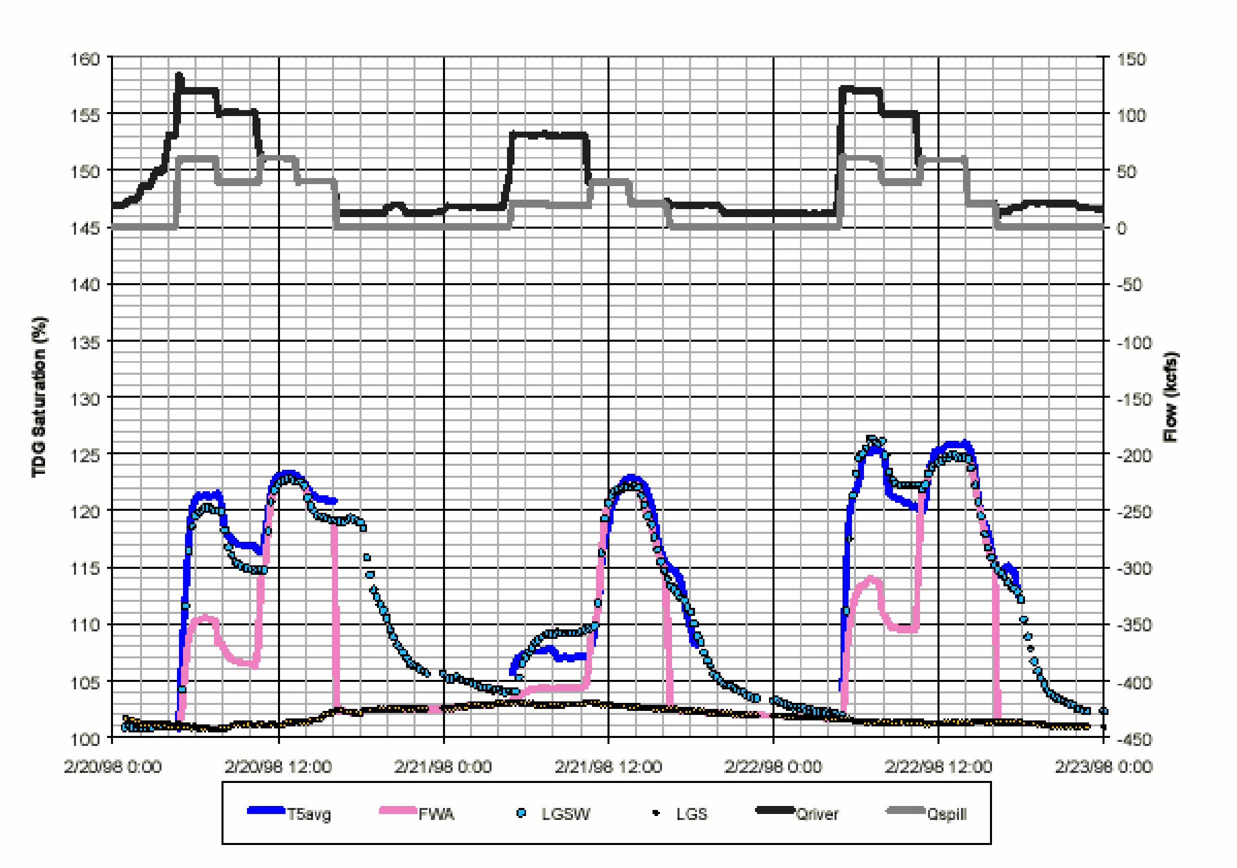

Figure 6. Project Operation and TDG Saturation at Little Goose Dam, February 1998. ($T5_{avg}$ Average TDG Level at Tailwater FMS, LGS- Forebay FMS, LGSW- Tailwater FMS, FWA- Flow Weighted Average Assuming No Entrainment)

The entrainment of powerhouse flow was modeled as a simple linear function of spillway discharge. The relationship shown in Equation 10 was used to estimate the entrainment discharge for each project. The coefficients C_1 and C_2 are project-specific constants. The entrainment of powerhouse flow was assumed to be exposed to the same conditions that spillway releases encounter and, hence, achieve the same TDG pressures.

$$Q_e = C_1 Q_{sp} + C_2 \qquad \text{Equation 10}$$

The loading capacity of the river segments identified for this TMDL are the water quality standard, namely 110 percent of saturation relative to atmospheric pressure.

Identification of Sources

There are four major sources of TDG within the geographic scope of this TMDL. They are:

1. Lower Granite Dam
2. Little Goose Dam
3. Lower Monumental Dam
4. Ice Harbor Dam

Other potential minor sources of elevated TDG in the Lower Snake River include: increases in TDG caused by natural changes in barometric pressure, temperature, or biological activity; and tributary sources of TDG (Palouse Falls).

Measurements of TDG in the water above Lower Granite Dam, which are the closest to the upstream boundary of this TMDL, occasionally exceed the TDG standard. The source of these elevated levels is not clear. Review of FMS data indicates that TDG levels from the Dworshak or the Hells Canyon Dams are not sufficiently elevated to be responsible for the high downstream levels. This suggests that the cause may be related to solar heating and photosynthesis in the Lower Granite pool.

This TMDL addresses those loads of TDG introduced by dams on the Lower Snake River that fall within Washington below the confluence of the Snake and Clearwater rivers. The cause of elevated TDG measurements above Lower Granite Dam and the Idaho border is unknown and will require future study.

The discussion of gas generation at each dam provided in this section is based on the U.S. Army Corps of Engineers analysis reported in the DGAS report (USACE, 2001a) and other sources. The information is provided to illustrate processes at the dams with their configuration at the time of the studies described. As structural modifications are made at the dams, the specific gas generation equations will change.

Analysis of Current Conditions

Data Sources

TDG data were available on many of the projects from several sources: the fixed monitoring station (FMS) system; near field (tailrace) and spillway performance tests; and in-pool transport and dispersion tests. Operational data were obtained from each project detailing the individual spillway and turbine discharge on an interval ranging from five minutes to one hour. These sources of data are discussed below. With these data sources, the most appropriate analysis was selected for each project. Individual mathematical relationships were developed on a project-by-project basis.

Data Quality

TDG data collected in the Snake River has undergone rigorous evaluation for data quality. For the TDG controlled spill studies, Wilhelms, Carroll, and Schneider (1997) reported on a workshop attended by a team of experts who evaluated the quality of data collections and recommended area for improvement. The workshop built on previous data quality evaluations.

The U.S. Army Corps of Engineers Walla Walla District office collects FMS data for the Snake River. Basic data quality procedures are provided in the annual Plan of Action (e.g., USACE, 2001b). Data collection methods and quality assurance procedures have been established for the Columbia and Snake Rivers FMS system (e.g., Tanner and Johnston, 2001). The Corps annual water quality reports provide detailed data quality analysis (e.g., USACE, 2000). The TDG data quality target for the FMS stations is a precision of no greater than one percent for paired readings.

In general, the data quality assurance/quality control procedures for the source information used in this TMDL meet or exceed the standards applied by the Washington State Department of Ecology for its own data collection and analysis for TMDL development.

The Fixed Monitoring Station (FMS) Data

The TDG data from the FMSs consisted of remotely monitored TDG pressure, dissolved oxygen, water temperature, and atmospheric pressure from a fixed location in the forebay and tailwater of each project. Data from the FMSs provide a long-term hourly record of TDG throughout the season, capturing detailed temporal and extreme events. However, the FMSs provide only limited spatial resolution of TDG distribution. In some cases, the TDG observed in the tailwater at the FMS location was not representative of average spillway conditions and misrepresented the TDG loading at a dam.

Spillway Performance Tests and Near-Field Studies

Spillway performance tests and near-field tailwater studies were conducted at several projects by the Corps to define the relationship between spill operation and dissolved gas production more clearly. Water temperature, TDG, and dissolved oxygen were monitored in the immediate tailrace region, just downstream of the project stilling basin. These observations provided a means to relate the local TDG saturation to spill operations directly, and to define gas transfer in different regions of the tailrace area. Studies were conducted at Lower Granite Dam in May and June 2002 (Schneider, 2002); Little Goose in February 1998 (Schneider and Wilhems, 1998a); Lower Monumental in August 1996 (Schneider and Wilhelms, 1996); and Ice Harbor in May and June 1996 (Schneider, 1996, and Schneider and Wilhems, 1997) and March 1998 (Schneider and Wilhems, 1998b).

In these studies, automated sampling of TDG pressures in spillway discharges during uniform and standard spill patterns was conducted with an array of instruments in the stilling basin and tailwater channel of the project. Automated sampling of TDG levels provide the opportunity to assess three-dimensional characteristics of the exchange of TDG immediately downstream of the stilling basin on a sampling interval ranging from five to 15 minutes. The integration of the distribution of flow and TDG pressure can yield estimates of the total mass loading associated with a given event. These tests were of short duration, generally lasting only several days and, therefore, pertain to the limited range of operations scheduled during testing.

In-Pool Transport and Dispersion Studies

During the 1996 spill season, in-pool transport and dispersion investigations were conducted to define the lateral mixing characteristics between hydropower and spillway releases. Water temperature, TDG levels, and dissolved oxygen were measured at several lateral transects located over an entire pool length. These studies focused on the lateral and longitudinal distribution of TDG throughout a pool during a period lasting from a few days to a week. In-pool transport and mixing studies were conducted below Little Goose, Lower Monumental, and Ice Harbor during the 1996 spill season. In most cases, a lateral transect of TDG instruments was located below the dam to establish the level of TDG entering the pool, with additional transects throughout the pool. These studies provided observations of the TDG saturation in project releases as they moved throughout an impoundment. However, only a limited range of operations was possible during the relatively short duration of these tests.

Operational Data

Operational data were obtained from each project detailing the spillway and powerhouse unit discharge on time intervals ranging from five minutes to one hour. The average hourly total spillway and generation releases, and forebay and tailwater pool elevations were summarized in the DGAS database. The tailwater pool gauge was generally located below the powerhouse of each dam. The tailwater elevation at the powerhouse was found to be within one foot of the water elevation downstream of the stilling basin in most instances.

Data Interpretation

The objective of this analysis was to develop mathematical relationships between observed TDG and operational parameters such as discharge, spill pattern, and tailwater channel depth. These relationships were derived with observations from the FMSs and spillway performance tests. However, before the analysis could be conducted, the monitored data had to be evaluated to determine its reliability for this kind of analysis. For example, the monitored TDG data from the FMSs provide a basis for defining the effects of spillway operation on dissolved gas levels in the river below a dam, but the following limitations should be noted:

- The FMSs sample water near-shore, which may not reflect average TDG levels of the spill. The monitor sites were, in general, located on the spillway side of the river to measure the effects of spillway operation. However, with a non-uniform spill distribution and geometry across the gates of the spillway, the FMS may be more representative of the spillbays closest to the shore. Outside spillbays without flow deflectors can create elevated TDG levels downstream from these bays compared to adjacent deflectored bays. A spill pattern that dictates higher unit discharges on these outside bays can further elevate the TDG levels downstream of these bays relative to the releases originating from the deflectored interior bays.

- Depending upon the lateral mixing characteristics, the FMS downstream of a project may be measuring spillway releases that have been diluted with hydropower releases. Under most conditions, the TDG saturation of generation releases is less than the TDG level associated with spillway releases. The TDG at the tailwater FMS will be a function of the discharge and level of TDG from both generation and spillway releases. Obviously, if there is no spill, then the monitored TDG levels will reflect the TDG saturation released by the hydropower facility.

- Passage of generation flows through a power plant does not significantly change the TDG levels associated with this water. However, there can be a significant near-field entrainment of powerhouse flow by spillway releases at some projects, especially if flow deflectors are present. Observed data suggest that, under these conditions, some portion of the powerhouse discharges will be subjected to the same processes that cause absorption of TDG by spillway releases. In these cases, the TDG levels measured immediately downstream of a spillway will be associated with the spillway release plus some component of the powerhouse discharge.

The observations of tailwater TDG pressure need to be paired up with project operations to conduct an evaluation of the data. A set of filters or criteria were established to select correctly-paired data for inclusion in this analysis. The travel time for project releases from the dam to the tailwater FMS was typically less than two hours and steady-state tailwater stage conditions were usually reached within this time period. Thus, the data records were filtered to include data pairs corresponding with constant operations of duration greater than two hours to exclude data corresponding with unsteady flow conditions. This filtering criterion eliminated data associated with changing operations and retained only a single observation for constant operating conditions equal to three hours in duration.

- *Manual and Automated Inspections for Obviously Inaccurate Observations.* An automated search for values above or below expected extremes identified potential erroneous and inaccurate data in the database. These data were inspected and, if appropriate, excised from the database.

- *Comparison of Measurements from Forebay and Tailwater Instruments During Non-Spill Periods.* During the non-spill periods, downstream measurements should approach the forebay concentration when only the hydropower project is releasing water. Inspection of the data was conducted to identify errors when this condition was not met.

- *Comparison of Measurements from Redundant Tailwater TDG Monitors, if Available.* TDG tailwater data was rejected when measurements of two instruments at the same site varied by more than three percent saturation.

Lower Granite Dam

TDG Exchange

The spillway operation at Lower Granite often results in the highest increase in the TDG loading within the study area. This fact is mainly caused by the low ambient TDG conditions approaching the dam. During 1997, the forebay TDG pressure was generally about 800 mm Hg (107 percent) and the tailwater TDG pressure during peak forced spill events exceeded 1,000 mm Hg (133 percent). The resultant TDG levels transported to Little Goose often reached maximum levels of 950 mm Hg (127 percent) or a net 150 mm Hg (20 percent) increase in the average TDG pressure as a result of spillway operations. The absence of detailed near-field data below Lower Granite caused the description of project TDG exchange to be based solely on observations from the FMS. The seasonally low and relatively constant background TDG pressures in the forebay of Lower Granite provided a unique opportunity to quantify the impacts of spill operation at Lower Granite on TDG conditions in the lower Snake River.

The TDG exchange properties at Lower Granite were explored through the evaluation of data from the tailwater FMS. The data collected during the 1997 spill season was filtered to include only events associated with a constant spill operation of 3 hours. The data filtering resulted in a total of 98 independent observations as summarized in Table 3. The delta TDG pressure ranged from 61.4 to 266.9 mm Hg for these events. The unit spillway discharge ranged from 3.1 to 26.4 kcfs/bay and the tailwater depth ranged from 48.7 to 55.5 feet.

Table 3. Statistical Summary of Regression Variables for Lower Granite Dam

	Delta Pressure ΔP (mm Hg)	Unit Spillway Discharge q_s (kcfs/bay)	Tailwater Depth D_{tw} (ft)
Number	98	98	98
Minimum	61.4	3.1	48.7
Maximum	266.9	26.4	55.5
Average	166.3	9.4	52.4
Standard Deviation	46.0	4.2	1.4

Source: U.S. Army Corps of Engineers DGAS Study, Appendix G, p. G-13

Regression

The TDG production during spillway releases from Lower Granite as defined by $\Delta P = P_{tw} - P_{bar}$, was found to be proportional to the product of tailwater depth and an exponential function of the specific discharge as shown in Equation 11. Both of the coefficients determined by the nonlinear regression analysis were significant to the 99 percent confidence interval as shown in Table 4. This formulation explained much of the variability in the data with an r-squared of 0.93 and a standard error of 11.60 mm Hg. This relationship indicates that the upper limit for TDG exchange for large unit spillway discharge is influenced by the tailwater depth below Lower Granite. As the total river flow increases, the tailwater stage will increase and higher TDG pressures will be generated for the same spill operation. The storage in Little Goose pool can also influence the tailwater conditions below Lower Granite.

This equation also implies that increasing the unit spillway discharge will result in higher TDG pressures. The unit spillway discharge can be very high for debris spill at Lower Granite, resulting in high TDG pressures for relatively low total spillway discharges. The spill pattern at Lower Granite spillway has also changed during the study period to accommodate the operation of the surface bypass system. Other structural changes to the spillway at Lower Granite, such as the raised spillway weir, will also affect the spill pattern and resultant TDG exchange through changes to the average unit spillway discharge.

$$\Delta P = 5.307 D_{tw}(1 - e^{-0.1059 q_s}) \qquad \text{Equation 11}$$

Where:

ΔP = P_{tw} - P_{bar}

P_{tw} = TDG pressure at the tailwater FMS (mm Hg)

q_s = Flow-weighted unit spillway bay discharge (kcfs/bay)

D_{tw} = Tailrace channel depth (feet) (E_{tw} - E_{ch})

E_{tw} = Elevation of the tailwater (ft)

E_{ch} = Average elevation of the tailrace channel (320 fmsl[1])

P_{bar} = Barometric pressure at the tailwater FMS (mm Hg)

Table 4. Statistical Summary of Nonlinear Regression at Lower Granite, 1997 Spill Season

$\Delta P = c_1 * D_{tw} * (1 - \exp(c_2 * q_s))$ Number of Observations n=98 $r^2 = 0.93$ Std Error = 11.60 mm Hg				
Coefficient	Estimate from Regression	Standard Error	t-statistic	Probability
c_1	5.307	0.151	35.17	<0.0001
c_2	-0.106	0.0056	-19.02	<0.0001

Source: U.S. Army Corps of Engineers DGAS Study, Appendix G, p. G-14

[1] feet above mean sea level

The unit spillway discharge was plotted against the observed and calculated tailwater TDG pressure difference in Figure 7. The exponential relationship between the TDG pressure and specific discharge is evident in this figure as the TDG pressure approached an upper limit as the specific discharge becomes large. Much of the variability in the TDG pressure for a constant unit discharge can be accounted for by the variation in the tailrace channel depth.

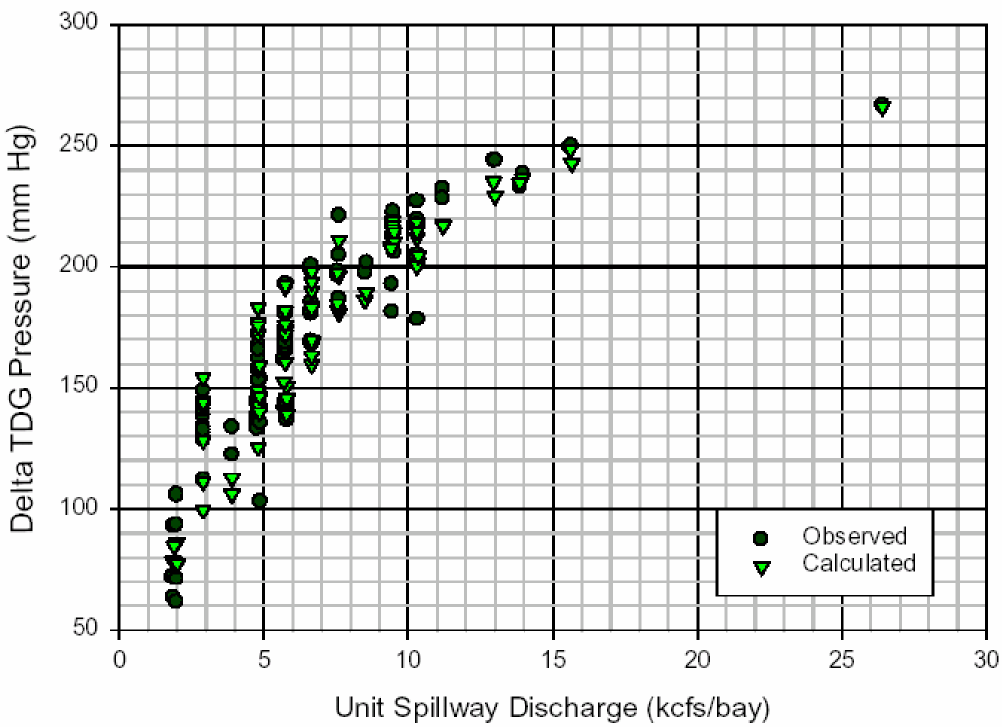

Figure 7. Unit Spillway Discharge versus TDG Pressure Above Barometric Pressure at Lower Granite Dam, 1997.

Most of the variability in the TDG production can be accounted for by the specific discharge. The specific discharge is a surrogate measure for the velocity, momentum, and exposure time of aerated flow associated with spillway discharge. The three-dimensional response surface for Equation 11 is shown in Figure 8 along with the observed data. The TDG pressure increases for a constant unit spillway discharge as the tailrace channel depth increases. However, the influence of the tailwater depth is small as evidenced by the small slope in the response surface for a constant unit discharge. The tailrace channel depth is a function of the total river flow and the pool elevation of the lower reservoir. This relationship couples the operation of the powerhouse at Lower Granite and the storage management in Little Goose pool to the TDG production in spillway releases from the Lower Granite spillway.

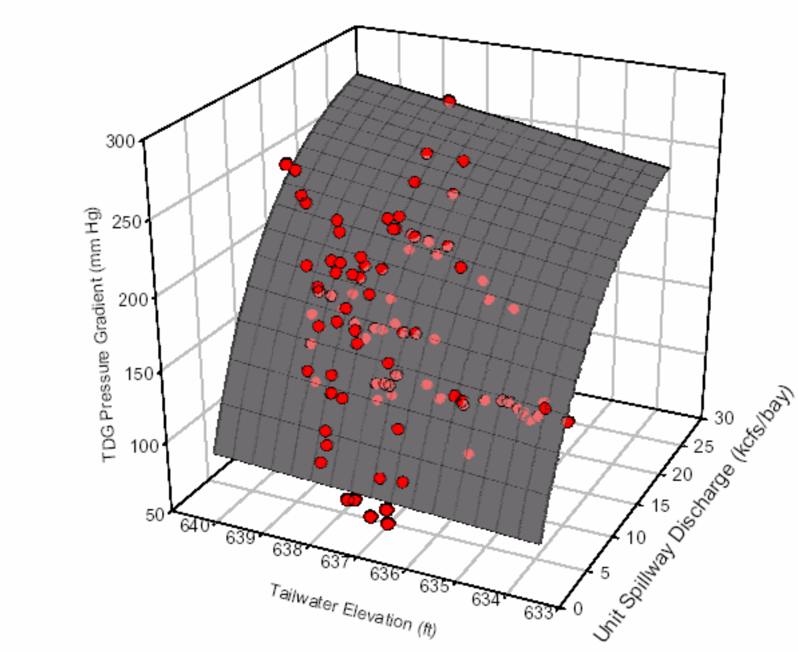

Figure 8. Unit Spillway Discharge, Tailwater Elevation, and TDG Pressure Above Barometric Pressure at Lower Granite Dam, 1997.

The response function as defined in Equation 11 was used to create a hindcast of the TDG production observed during the 1997 spill season. The hourly project operation and TDG pressure at the Lower Granite FMS's for the month of June 1997 are shown in Figure 9 along with the estimates of TDG saturation based on Equation 11. In general, the estimated TDG pressure was generally within 10 mm Hg of the observed tailwater TDG saturation. The tailwater TDG instrument malfunctioned during June 7-10, resulting in the large difference between observed and calculated values. The TDG production relationship could be used to screen data coming from the FMS system for the purpose of assuring the quality of information used for real time management decision-making. The occurrence of atypical spill patterns, measurement error, and dilution with powerhouse releases probably accounts for much of the estimation error shown during this period.

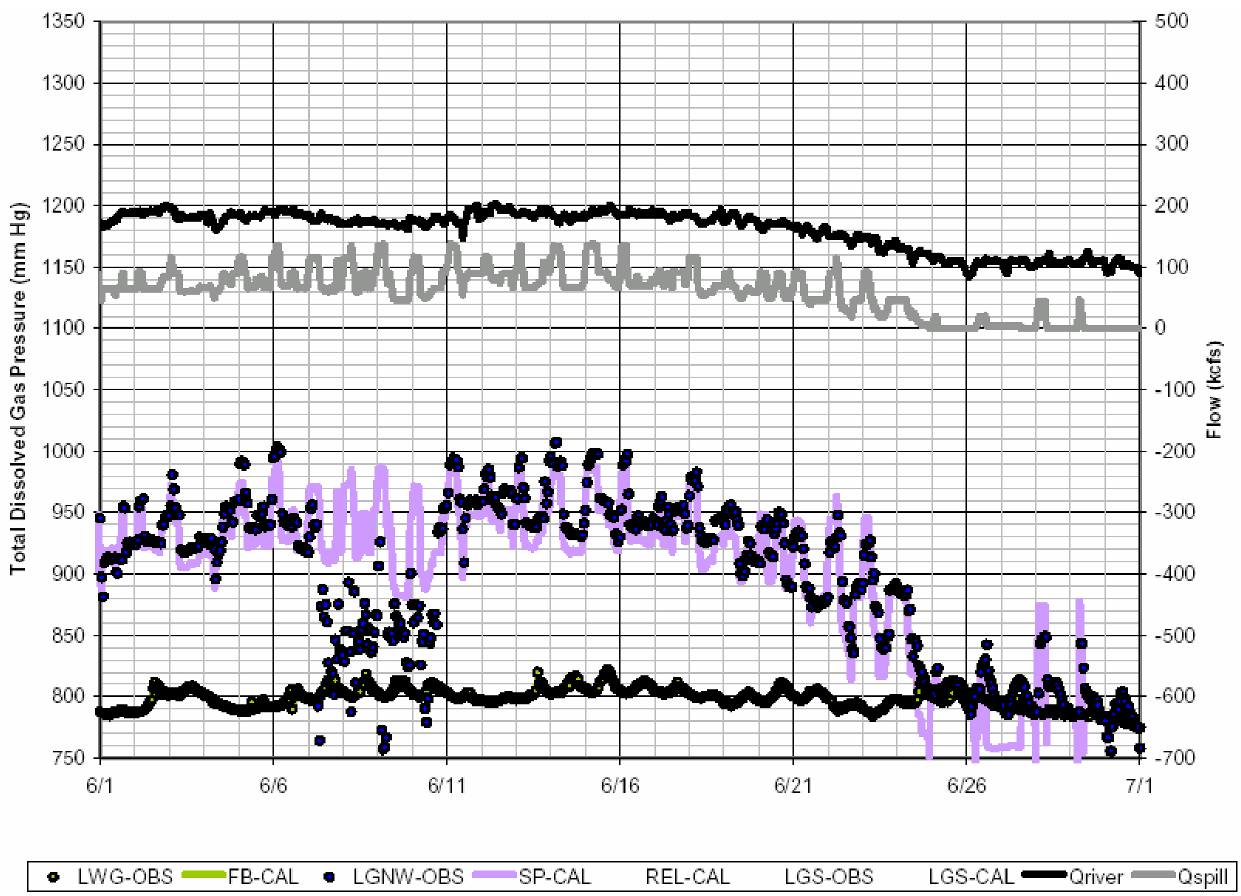

Figure 9. Observed and Estimated TDG Pressure at the Tailwater Fixed Monitoring Station at Lower Granite Dam, 1997.
(LGW-Obs Observed Forebay TDG , LGNW-Obs Observed Tailwater TDG, SP-Cal Calculated Tailwater TDG, Qriver-Hourly Total River Flow, Qspill-Hourly Spillway Flow)

Entrainment of Powerhouse Discharge

This formulation defined by Equation 11 does not account for the added mass of TDG associated with entrainment of powerhouse releases into the aerated flow regime below a spillway. The observations of surface flow patterns below Lower Granite have demonstrated the vigorous interaction that occurs between spillway and powerhouse releases. A recirculation cell has been observed to form directly below the Lower Granite powerhouse, which draws water back towards the powerhouse and promotes the lateral entrainment of powerhouse flows into the stilling basin.

The importance of the entrainment of powerhouse flows into the bubbly flow in the stilling basin was demonstrated by routing Lower Granite releases through the Little Goose pool for the historic conditions observed during 1997. The average TDG pressure generated by Lower Granite operations was estimated by using a flow-weighted average of powerhouse and spillway flows. The TDG content of spillway flows were determined from Equation 11 while the TDG pressure associated with powerhouse releases was set to the observed forebay TDG pressure. A simple hydrologic routing of project releases was performed to estimate the TDG pressure arriving at Little Goose.

The results from this analysis are shown in Figure 10 where the observed hourly TDG pressure at Little Goose (LGS-obs) is shown as the shaded circles while the estimated TDG pressure in the forebay of Little Goose (LGS-cal) is shown as a light pink line (the lower gray line in black-and-white copies). The difference between the estimated and observed TDG pressure was as is large as 80 mm Hg. The largest prediction errors tended to be associated with operating conditions resulting in a smaller percent of the river spilled. The simulation of TDG exchange was repeated using a simple linear relationship between spillway discharge and the estimated entrainment of powerhouse flow. The entrainment of powerhouse flow was assumed to equal 75 percent of the total spillway discharge as limited by available powerhouse releases. The entrained powerhouse flows were assumed to be exposed to the same conditions as spillway releases and experience comparable TDG uptake.

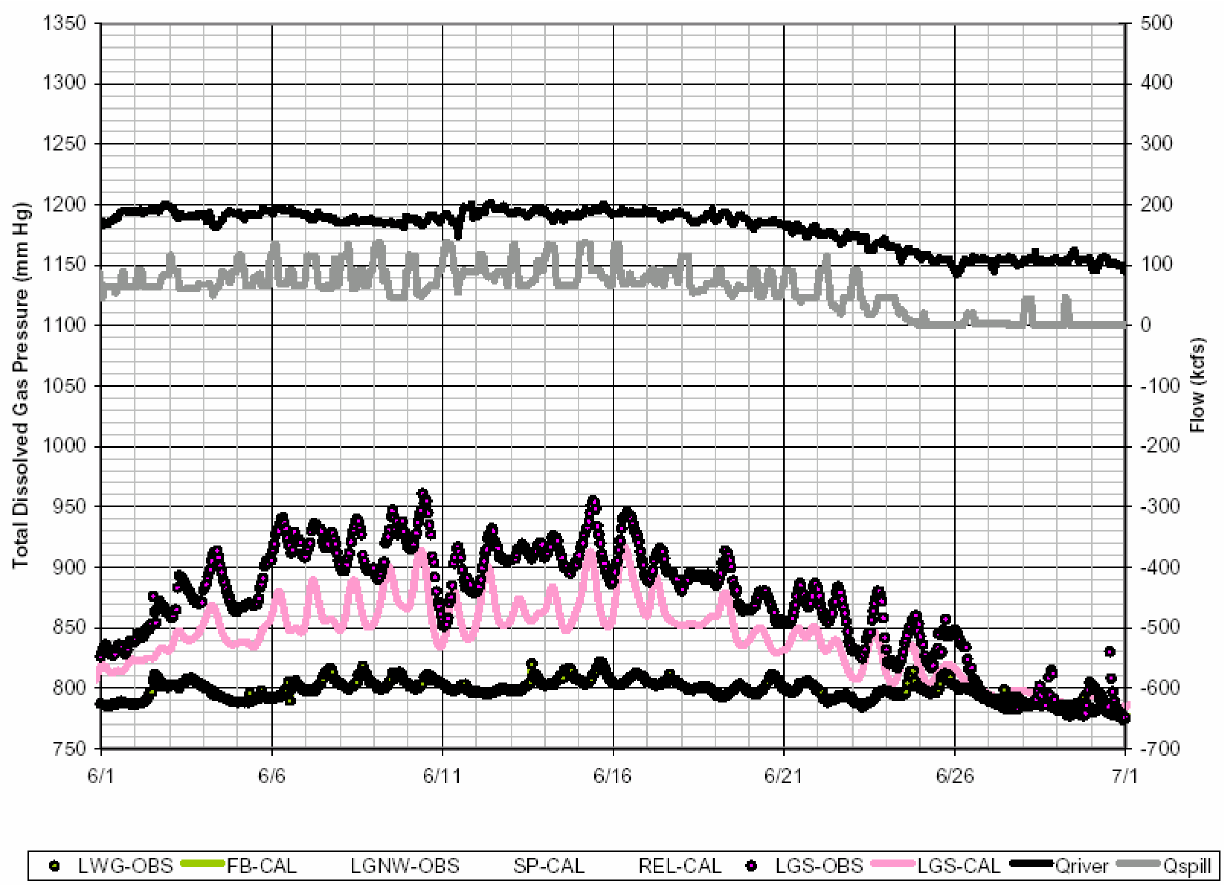

Figure 10. Observed and Estimated TDG Pressure in the Forebay of Lower Granite and Little Goose Dams, June 1997 (No Entrainment of Powerhouse Releases).

The results from this formulation for TDG exchange at Lower Granite are shown in Figure 11. The estimated TDG pressure in the Little Goose forebay much more closely predicted the observed TDG pressure throughout the month of June. The average prediction error was small for the simulation shown in Figure 11 with the peak TDG pressures well represented. The short travel time through Little Goose pool during this evaluation will lessen the influence of changing water temperatures and TDG exchange across the water surface on TDG pressure. As a consequence of this evaluation, the effective spillway flow (actual+entrainment) was estimated to be about 175 percent of the rated spillway release. The effective spillway discharge at Lower Granite can be calculated as Qse=1.75Qs provided that the powerhouse flows exceed the entrainment discharge.

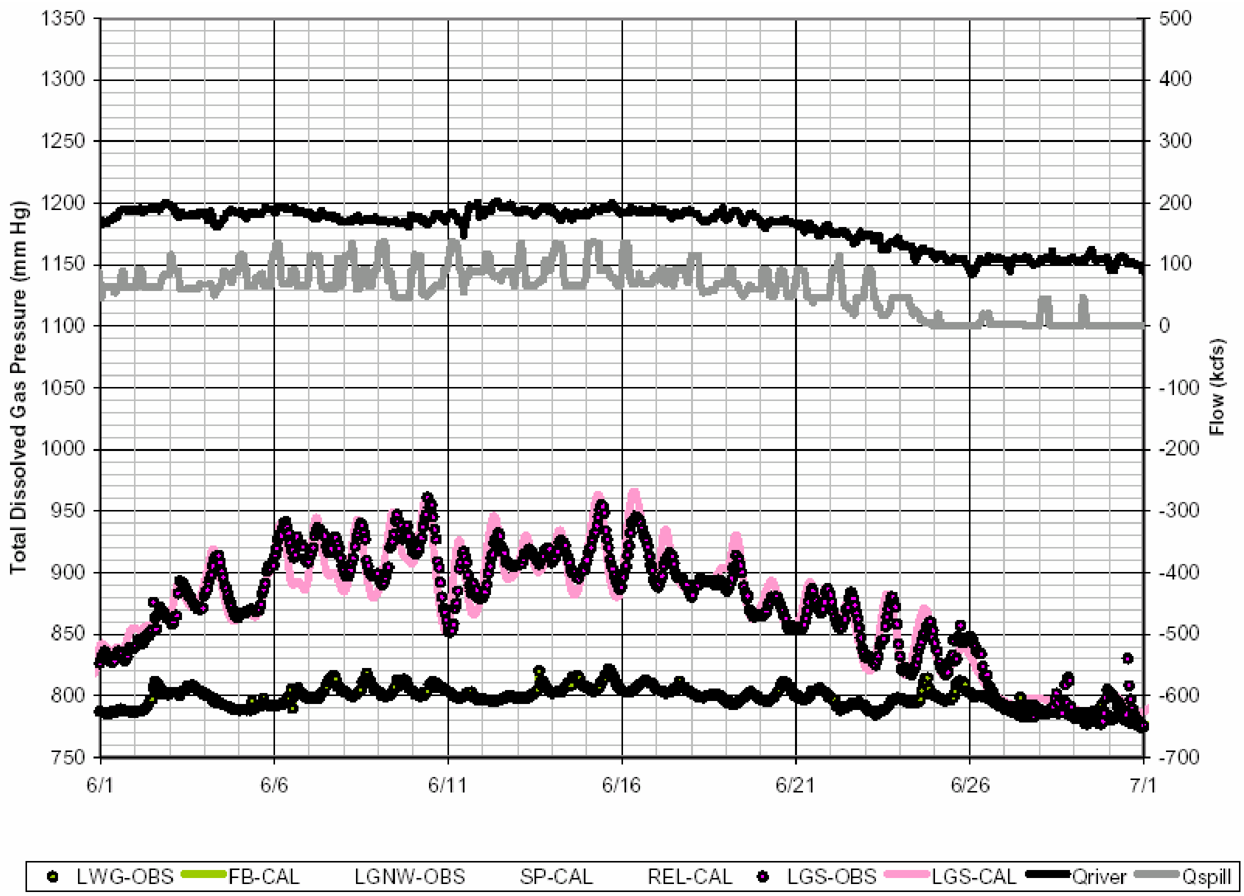

Figure 11. Observed and Estimated TDG Pressure in the Forebay of Lower Granite and Little Goose Dams, June 1997 (Powerhouse Entrainment=0.75 Q_s).

Little Goose Dam

TDG Exchange

A near-field TDG exchange investigation was conducted at Little Goose during February 20-22, 1998, as described in Schneider and Wilhelms (1998a). The study consisted of sampling TDG pressures below the spillway during spillway discharges ranging from 20 to 60 kcfs with and without powerhouse flows. Two different spill patterns were investigated during this study--adult and juvenile spill patterns. The study findings indicated that the TDG production was directly related to the unit spillway discharge, spill pattern, and powerhouse flow. The resultant average TDG saturation in Little Goose project flows ranged from 110 to 127 percent during the study for unit spillway discharges ranging from 2.5 to 10 kcfs/bay. The operation of all eight bays (adult pattern) was found to increase the TDG exchange when compared to the juvenile pattern (only bays with flow deflectors) at similar unit spillway flows by as much as 5 percent saturation. The presence of ambient TDG pressures associated with powerhouse releases was not observed downstream of the highly aerated flow regime associated with Little Goose spill, implying considerable lateral interaction of project releases. In the case of the adult spill pattern at a discharge of 40 and 60 kcfs, the addition of a powerhouse flow of 60 kcfs with forebay TDG saturation of 101 percent did not change the average TDG saturation below Little Goose of 123 and 126 percent, respectively.

Regression

The TDG exchange at Little Goose was further explored through the evaluation of data from the FMS. This evaluation provided a wider range of operating conditions in terms of spillway discharge and tailwater elevation than observed during the near-field test. The regression equation was based on data collected during the 1997 spill season for spills using the juvenile spill pattern (spill was limited to the six internal spillway bays). The filtered data resulted in a total of 190 independent observations as listed in Table 5. The delta TDG pressure ranged from 79.6 to 218.8 mm Hg for these events. The unit spillway discharge ranged from 1.8 to 21.6 kcfs/bay and the tailwater depth ranged from 36.3 to 42.1 feet.

Table 5. Statistical Summary of Regression Variables

	Delta Pressure ΔP (mm/Hg)	Unit Spillway Discharge q_s (kcfs/bay)	Tailwater Depth D_{tw} (ft)
Number	190	190	190
Minimum	79.6	1.8	36.3
Maximum	218.8	21.6	42.1
Average	158.4	9.5	39.0
Standard Deviation	29.0	3.5	1.3

Source: U.S. Army Corps of Engineers DGAS Study, Appendix G, p. G-17

The TDG production during spillway releases using the juvenile spill pattern from Little Goose, as defined by $\Delta P = P_{tw} - P_{bar}$, was found to be proportional to the product of tailwater depth and an exponential function of an exponential function of the unit spillway discharge as shown in Equation 12. Both of the coefficients determined by the nonlinear regression analysis were significant to the 99 percent confidence interval as shown in Table 6. This formulation explained much of the variability in the data with an r-squared of 0.84 and a standard error of 11.65 mm Hg. Several data points were responsible for the poorer correlation coefficient for this data set compared to the other projects.

$$\Delta P = 5.566 D_{tw}(1 - e^{-0.150 q_s})$$ Equation 12

Where:

ΔP	=	$P_{tw} - P_{bar}$
P_{tw}	=	TDG pressure at the tailwater FMS (mm Hg)
P_{bar}	=	Barometric pressure at the tailwater FMS (mm Hg)
q_s	=	Flow-weighted unit spillway bay discharge (kcfs/bay)
D_{tw}	=	Tailrace channel depth (feet) (E_{tw}-E_{ch})
E_{tw}	=	Elevation of the tailwater (fmsl)
E_{ch}	=	Average elevation of the tailrace channel (500 fmsl)

Table 6. Statistical Summary of Nonlinear Regression at Little Goose, Juvenile Spill Pattern, 1997 Spill Season

$\Delta P_{tw} = c_1 * D_{tw} * (1 - \exp(c_2 * q_s))$ Number of observations n=190 $r^2 = 0.84$ Std. Error=11.65 mm Hg				
Coefficient	Estimate from Regression	Standard Error	t-statistic	Probability
c_1	5.566	0.0996	55.91	<0.0001
c_2	-0.150	0.0060	24.91	<0.0001

Source: U.S. Army Corps of Engineers DGAS Study, Appendix G, p. G-18

The unit spillway discharge was plotted against the observed and calculated tailwater delta TDG pressure in Figure 12. The exponential relationship between the TDG pressure and specific discharge is evident in this figure as the TDG pressure approached an upper limit as the specific discharge becomes large. Much of the variability in the TDG pressure for a constant unit discharge can be accounted for by the variation in the tailrace channel depth. The degree of TDG exchange will approach a threshold value only for a constant tailwater depth using this formulation. Since the tailwater depth will continue to increase for higher river flows during forced spill conditions, the limit for TDG exchange will also continue to increase.

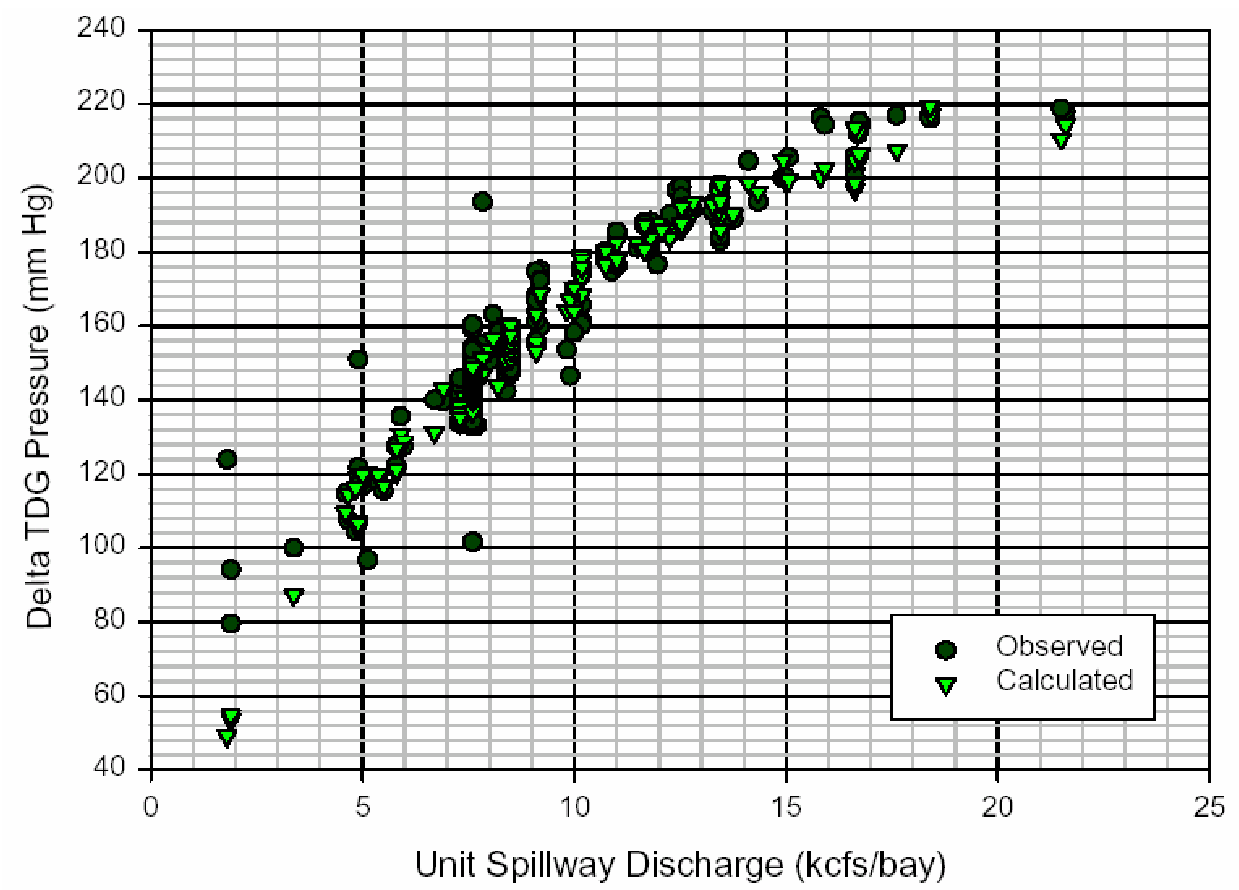

Figure 12. Unit Spillway Discharge versus TDG Pressure above Barometric Pressure at Little Goose Dam, Juvenile Spill Pattern, 1997.

Most of the variability in the TDG production can be accounted for by the unit spillway discharge. The specific discharge is a surrogate measure for the velocity, momentum, and exposure time of aerated flow associated with spillway discharge. The three-dimensional response surface for Equation 12 is shown in Figure 13 along with the filtered observed FMS data. The TDG pressure increases for a constant unit spillway discharge as the tailrace channel depth increases. However, the influence of the tailwater depth is small as evidenced by the small slope in the response surface for a constant unit discharge. The tailrace channel depth is a function of the total river flow and the pool elevation of the lower reservoir. This relationship couples the operation of the powerhouse at Little Goose and the storage management in Lower Monumental pool to the TDG production in spillway releases from the Little Goose spillway.

The response function as defined in Equation 12 was used to create a hindcast of the TDG production observed during the 1997 spill season. The hourly project operation and TDG saturation at the Little Goose FMS's (LGS-forebay, LGSW-tailwater) for the month of May 1997 are shown in Figure 14 along with the estimates of tailwater TDG saturation (TDGest) based on Equation 12. In general, the estimated TDG saturation was generally within 1 percentage point of the observed tailwater TDG saturation during the juvenile spill events. The scheduling of the adult spill pattern is indicated by the positive discharge through bay 8 (Qs8). In general, the tailwater TDG pressure dropped below 120 percent only during juvenile spill events of 40

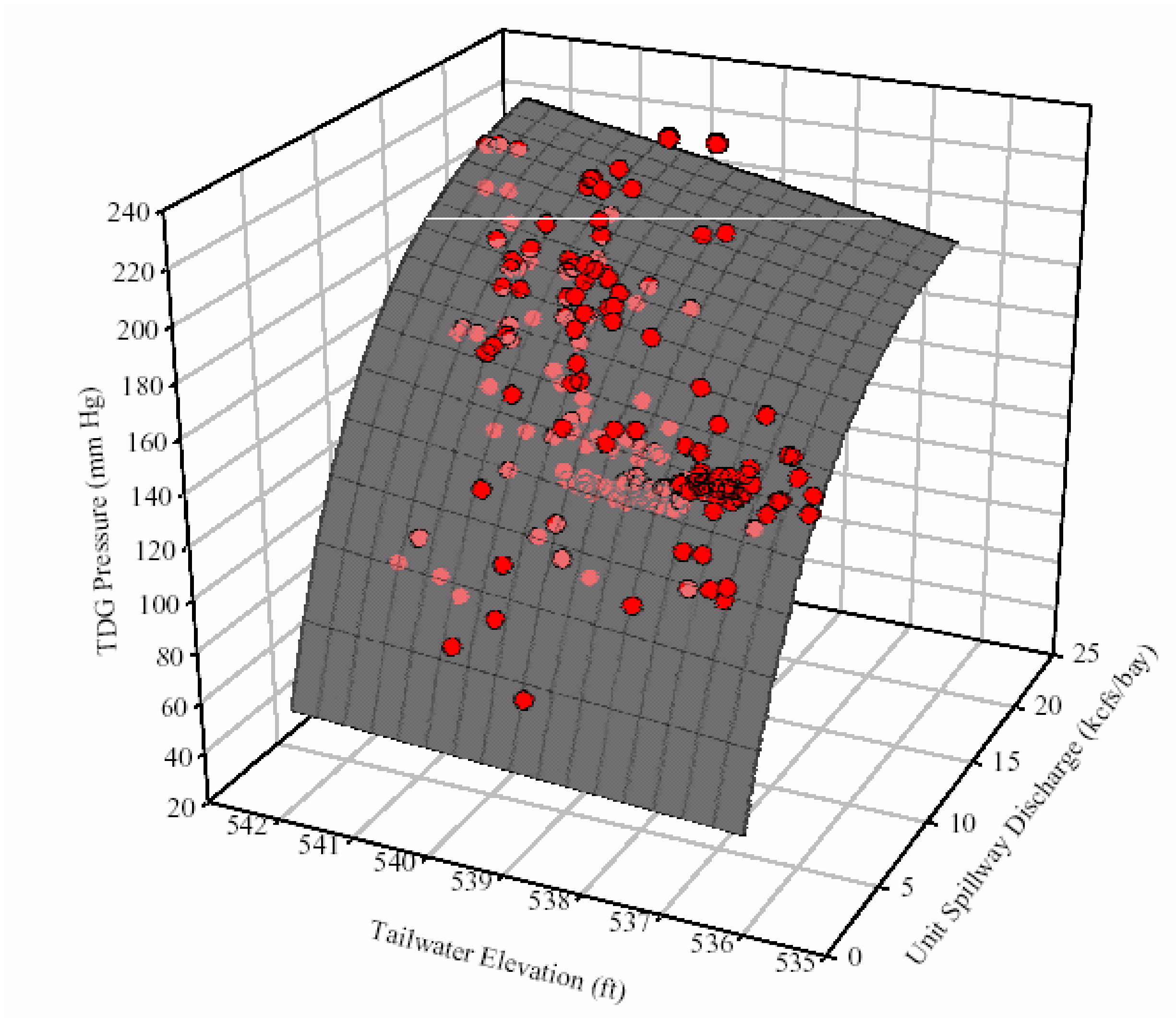

Figure 13. Unit Spillway Discharge, Tailwater Elevation, and TDG Pressure Above Barometric Pressure at Little Goose Dam, 1997.

kcfs or less. The tailwater TDG saturation exceeded 130 percent during juvenile spill releases approaching 100 kcfs. Large differences between the observed and calculated TDG saturations were observed prior to May 10. These differences were most likely due to instrument malfunction during this period.

The operations of all spillway bays in the adult spill pattern with a constant operation of 3 hours were identified during the 1997 spill season for Little Goose. This data filtering resulted in a total of only 35 independent hourly observations. The delta TDG pressure was found to range from 65.6 to 276.6 mm Hg as listed in Table 7. The range in unit spillway discharge was from 1.9 to 13.2 kcfs/bay and the tailwater depth ranged from 38.5 to 41.7 feet.

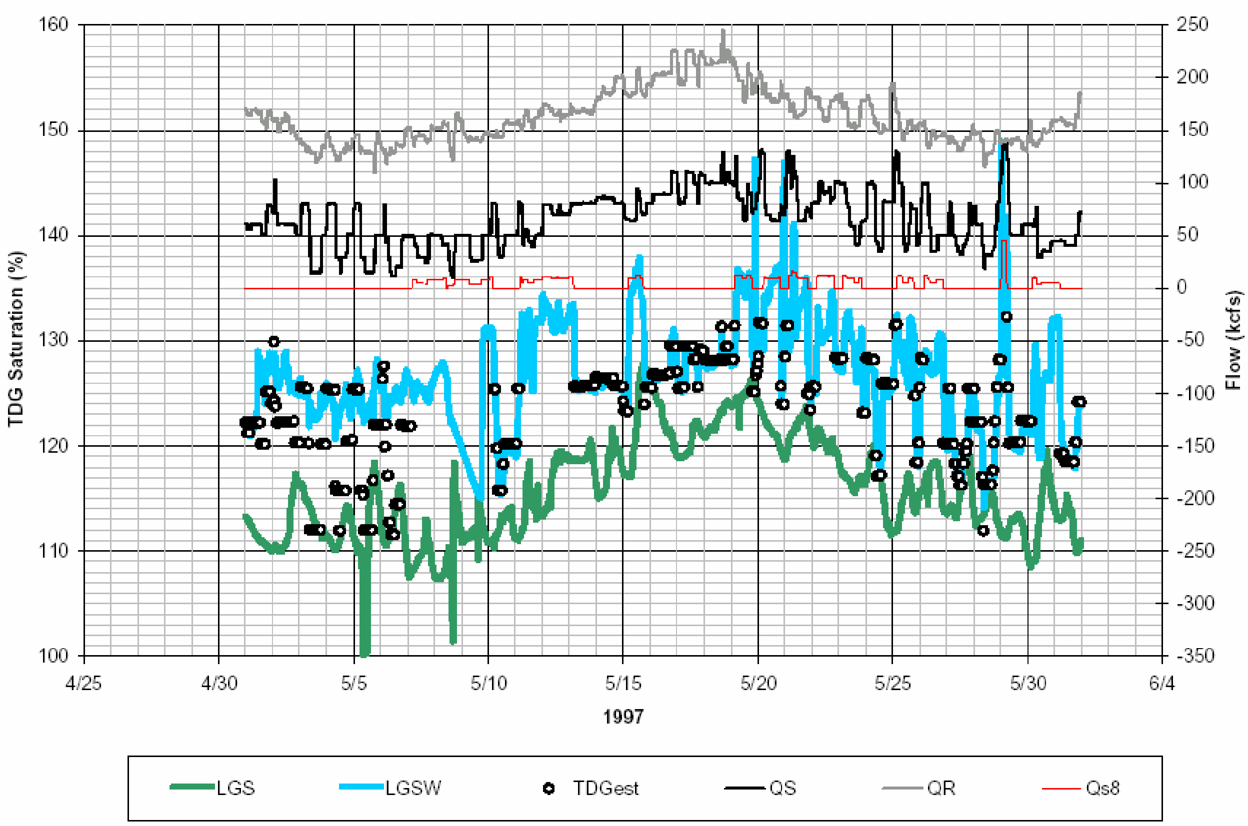

Figure 14. Observed and Estimated TDG Saturation at the Tailwater Fixed Monitoring Station at Little Goose Dam, 1997.
(LGS=Observed Forebay TDG, LGSW=Observed Tailwater TDG, LGSWest =Calculated Tailwater, TDG,QR=Hourly Total River Flow, QS=Hourly Spillway Flow)

Table 7. Statistical Summary of Regression Variables

	Delta Pressure ΔP (mm Hg)	Unit Spillway Discharge q_s (kcfs/bay)	Tailwater Depth D_{tw} (ft)
Number	35	35	35
Minimum	65.6	1.9	38.5
Maximum	276.6	13.2	41.7
Average	222.4	7.9	40.2
Standard Deviation	42.0	2.8	0.8

Source: U.S. Army Corps of Engineers DGAS Study, Appendix G, p. G-19

The functional relationship for the TDG production of the adult spill pattern (all eight bays) was similar to the equation determined for spillway bays with flow deflectors at Little Goose as shown in Equation 13. All of the coefficients determined by the nonlinear regression analysis were significant to the 99 percent confidence interval as shown in Table 8. This formulation contained a much higher standard error (19.5 mm Hg) than found in other production relationships with an r-squared of 0.79. The observed and calculated delta TDG pressures were plotted against the unit spillway discharge at Little Goose in Figure 15.

$$\Delta P = 6.488 D_{tw}(1 - e^{-0.280 q_s}) \qquad \text{Equation 13}$$

Table 8. Statistical Summary of Nonlinear Regression at Little Goose, Adult Spill Pattern, 1997 Spill Season

$\Delta P_{tw} = c_1 * D_{tw} * (1 - \exp(c_2 * q_s))$ Number of observations n=35 $r^2 = 0.79$ Std. Error = 19.51 mm Hg				
Coefficient	Estimate from Regression	Standard Error	t-statistic	Probability
c_1	6.488	0.2197	29.5268	<0.0001
c_2	0.2796	0.0319	8.7538	<0.0001

Source: U.S. Army Corps of Engineers DGAS Study, Appendix G, p. G-19

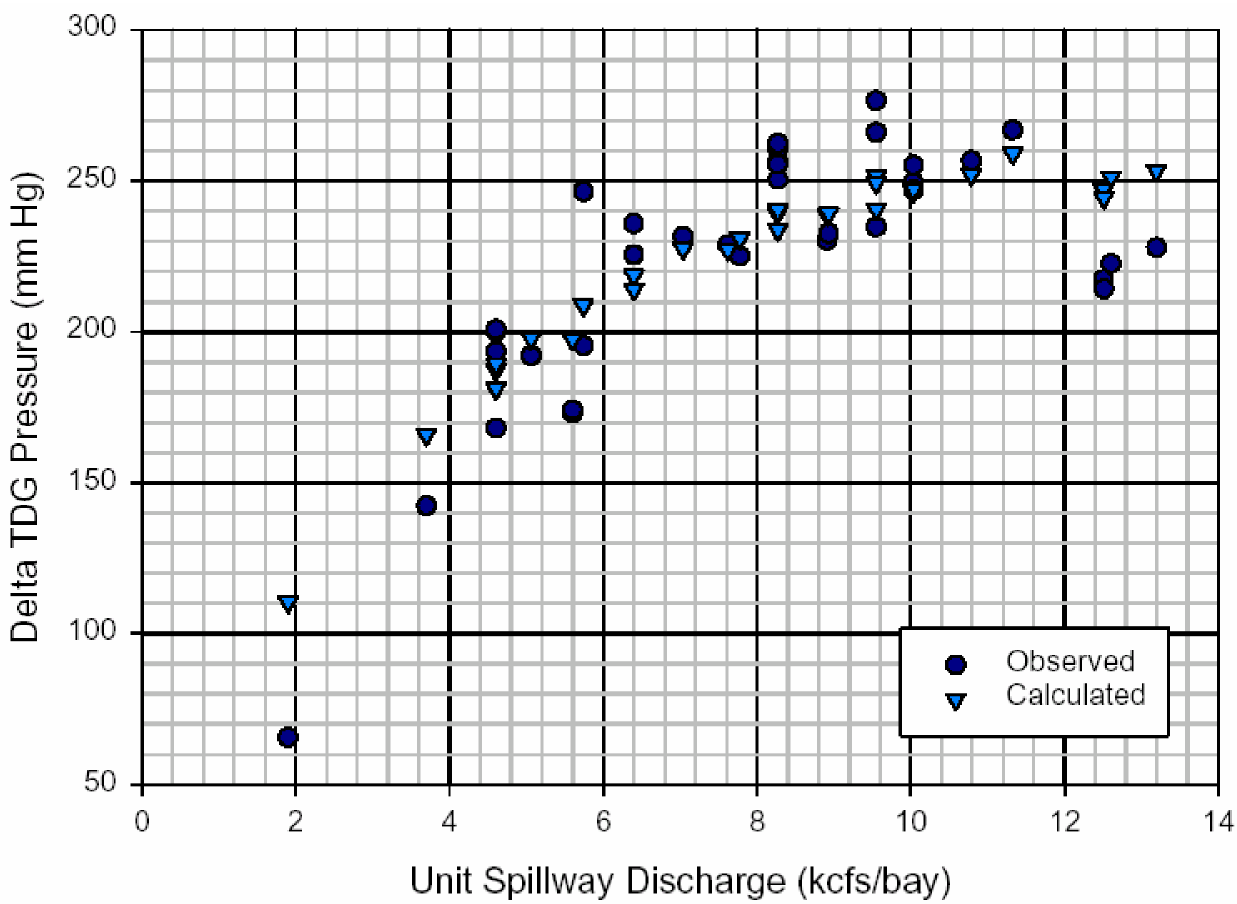

Figure 15. Unit Spillway Discharge versus TDG Pressure Above Barometric Pressure at Little Goose Dam, Adult Spill Pattern, 1997.

Entrainment of Powerhouse Discharge

The determination of the fate of powerhouse flow was documented during the TDG exchange study conducted at Little Goose (Schneider and Wilhelms, 1998a). The entrainment of powerhouse flows into the bubbly flow in the stilling basin is significant below Little Goose and has been estimated to be a function of the spillway discharge. The effective spillway flow (actual+entrainment) has been greater than 200 percent of the rated spillway release. The effective spillway discharge at Little Goose can be estimated as Qe=1.0Qs provided that the powerhouse flows exceed the entrainment discharge.

This functional form for the entrainment discharge was applied to observed data during the 1997 spill season at Little Goose. The average TDG pressure generated by Little Goose operations was estimated by using a flow-weighted average of powerhouse and spillway flows. The TDG content of spillway flows was determined from Equation 13 and while the TDG pressure associated with powerhouse releases was set to the observed forebay TDG pressure. A simple hydrologic routing of project releases was performed to estimate the TDG pressure arriving at Lower Monumental. No entrainment of powerhouse flows was assumed for the first scenario. The results from this analysis are shown in Figure 16 where the observed hourly TDG pressure

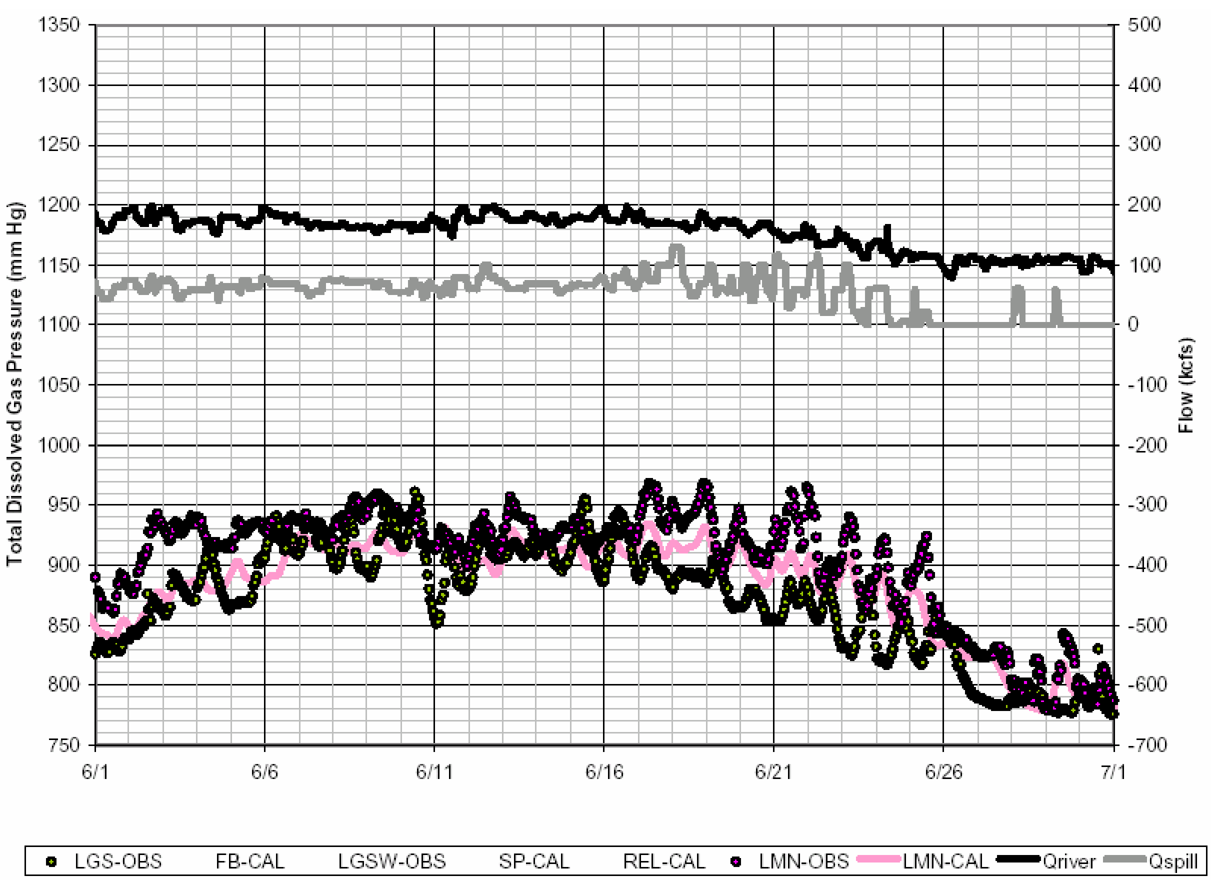

Figure 16. Project Operations and Observed and Calculated TDG Pressures in the Forebay of Lower Monumental Dam, June 1997 (No entrainment of Little Goose Dam Powerhouse Flows).

in the forebay of Lower Monumental (LMN-obs) is shown as shaded circles while the estimated TDG pressure in the forebay of Lower Monumental (LMN-cal) is shown as a light pink line (the lower gray line in black-and-white copies). The difference between the estimated and observed TDG pressure was as large as 50 mm Hg and was consistently less than observed conditions throughout the month of June.

The simulation of TDG exchange and transport was repeated using a simple linear relationship between spillway discharge and the estimated entrainment of powerhouse flow. The entrainment of powerhouse flow was assumed to equal to the spillway discharge as limited by available powerhouse releases. The entrained powerhouse flows were assumed to be exposed to the same conditions as spillway releases and to experience comparable TDG uptake. The results from the simulation with entrainment are shown in Figure 17. The calculated TDG pressure much more closely approximates the observed TDG pressures in the forebay of Lower Monumental. This evaluation agrees closely with the finding from the near-field TDG study, which indicated a significant component of powerhouse releases is exposed to aerated flow conditions and TDG exchange processes.

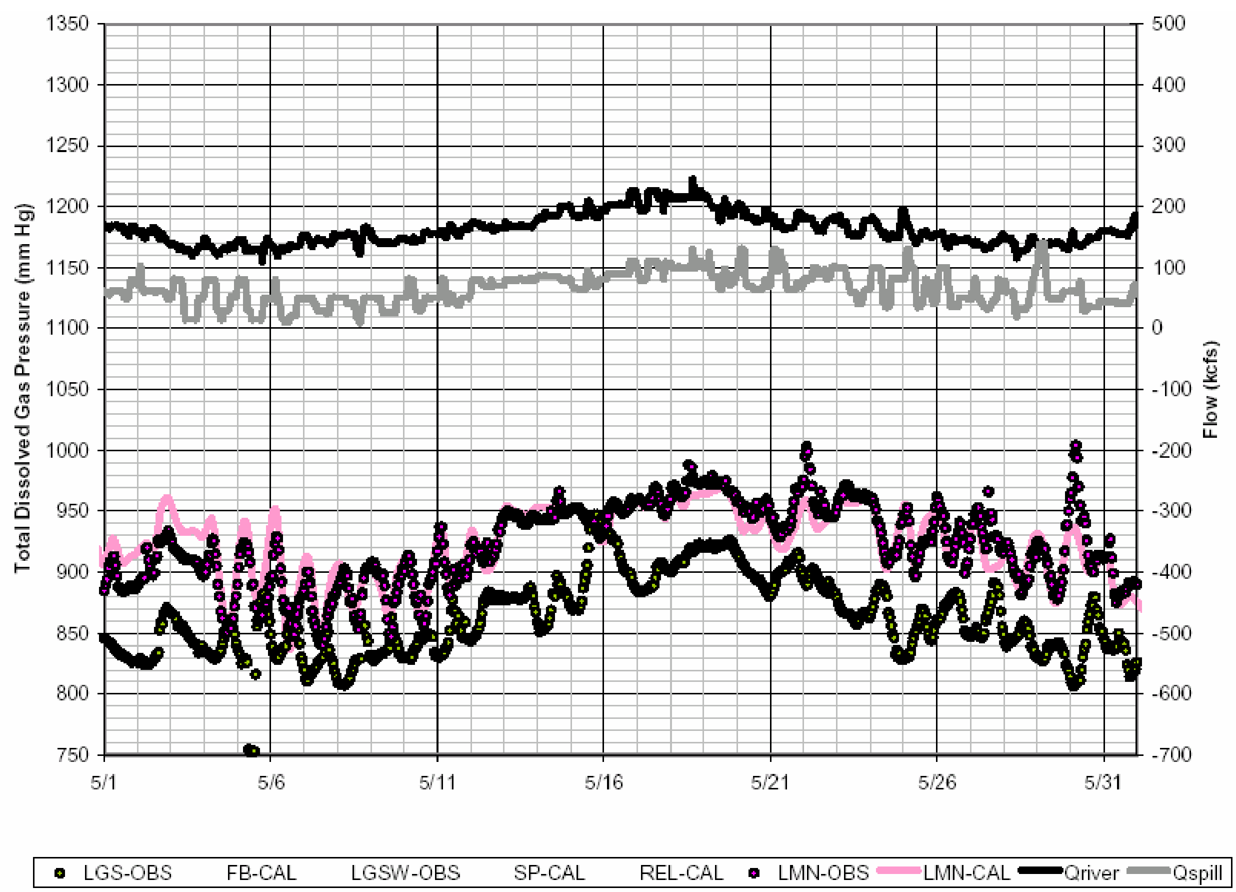

Figure 17. Project Operations and Observed and Calculated TDG Pressures in the Forebay of Lower Monumental Dam, June 1997 (Entrainment of Little Goose Dam Powerhouse Flows=Spillway Discharge).

Lower Monumental Dam

TDG Exchange

A TDG exchange field investigation was conducted at Lower Monumental during August 21-22, 1996, with the study summarized in Schneider and Wilhelms (1996). The study consisted of sampling TDG pressures below the spillway during spillway discharges ranging from 10 to 50 kcfs. Two different spill patterns were investigated during this study--adult and juvenile spill patterns. The study findings indicated that the TDG production was directly related to the unit spillway discharge. The TDG saturation ranged from 105 to 121 percent during the study for unit spillway discharges ranging from 1.3 to 8.4 kcfs/bay. The influence of the operation of spillway bays without flow deflectors was found to increase the TDG exchange for comparable unit spill discharges by as much as 9 percent saturation. The relatively small total river flows and associated range in tailwater elevations resulted in test spill conditions corresponding with tailwater elevations ranging from 438.6 to 439.9 fmsl.

An evaluation of data from the tailwater FMS during 1997 provided an opportunity to study the TDG exchange of spillway flows at Lower Monumental under a wider range of operating conditions. The spillway events were identified by the applied spill pattern and separate evaluations were conducted for these types of events. The data associated with spill over bays with flow deflectors with a constant operation of 3 hours were identified. This data filtering resulted in a total of 68 independent hourly observations. The delta TDG pressure was found to range from 101.9 to 238.7 mm Hg as listed in Table 9. The range in unit spillway discharge was from 2.1 to 24.1 kcfs/bay and the tailwater depth ranged from 42.7 to 48.1 feet.

Table 9. Statistical Summary of Regression Variables

	Delta Pressure ΔP (mm Hg)	Unit Spillway Discharge q_s (kcfs/bay)	Tailwater Depth D_{tw} (ft)
Number	68	68	68
Minimum	101.9	2.1	42.7
Maximum	238.7	24.1	48.1
Average	205.1	13.3	44.6
Standard Deviation	25.6	4.8	1.1

Source: U.S. Army Corps of Engineers DGAS Study, Appendix G, p. G-21

Regression

The functional relationship between TDG production and project operation at Lower Monumental was similar to Little Goose. The TDG pressure in excess of the local barometric pressure, as defined by $\Delta P = P_{tw} - P_{bar}$, was found to be proportional to the product of tailwater depth and an exponential function of the specific discharge as shown in Equation 14. All of the coefficients determined by the nonlinear regression analysis were significant to the 99 percent confidence interval as shown in Table 10. This formulation explained much of the variability in the estimated dependent variable with an r-squared of 0.96 and a standard error of 5.4 mm Hg.

$$\Delta P = 5.056 D_{tw}(1 - e^{-0.210 q_s}) \qquad \text{Equation 14}$$

Where:

ΔP = $P_{tw} - P_{bar}$
P_{tw} = TDG pressure at the tailwater FMS (mm Hg)
P_{bar} = Barometric pressure at the tailwater FMS (mm Hg)
q_s = Flow-weighted unit spillway bay discharge (kcfs/bay)
D_{tw} = Tailrace channel depth (feet) (E_{tw}-E_{ch})
E_{tw} = Elevation of the tailwater (fmsl)
E_{ch} = Average elevation of the tailrace channel (500 fmsl)

Table 10. Statistical Summary of Nonlinear Regression at Lower Monumental, Juvenile Spill Pattern, 1997 Spill Season

$\Delta P_{tw} = c_1 * D_{tw} * (1 - \exp(c_2 * q_s))$ Number of observations n=68 $r^2 = 0.96$ Std. Error = 5.4 mm Hg					
Coefficient		Estimate from Regression	Standard Error	t-statistic	Probability
Deflectored bays	c_1	5.056	0.0306	165.3989	<0.0001
	c_2	-0.21	0.0060	35.8829	<0.0001

Source: U.S. Army Corps of Engineers DGAS Study, Appendix G, p. G-22

The unit spillway discharge was plotted against the observed and calculated tailwater TDG pressure above the local barometric pressure as shown in Figure 18. The exponential relationship between the TDG pressure and specific discharge is evident in this figure as the TDG pressure approached an upper limit as the specific discharge becomes large. Much of the variability in the TDG pressure for a constant unit discharge can be accounted for by the variation in the tailrace channel depth.

Most of the variability in the TDG production can be accounted for by the specific discharge. The specific discharge is a surrogate measure for the velocity, momentum, and exposure time of aerated flow associated with spillway discharge. The three-dimensional response surface for Equation 14 is shown in Figure 19 along with the observed data. The TDG pressure increases for a constant unit spillway discharge as the tailrace channel depth increases. However, the influence of the tailwater depth is small as evidenced by the small slope in the response surface for a constant unit discharge. The tailrace channel depth is a function of the total river flow and the pool elevation of the lower reservoir. This relationship couples the operation of the powerhouse at Lower Monumental and the storage management in Ice Harbor pool to the TDG production in spillway releases from the Lower Monumental spillway.

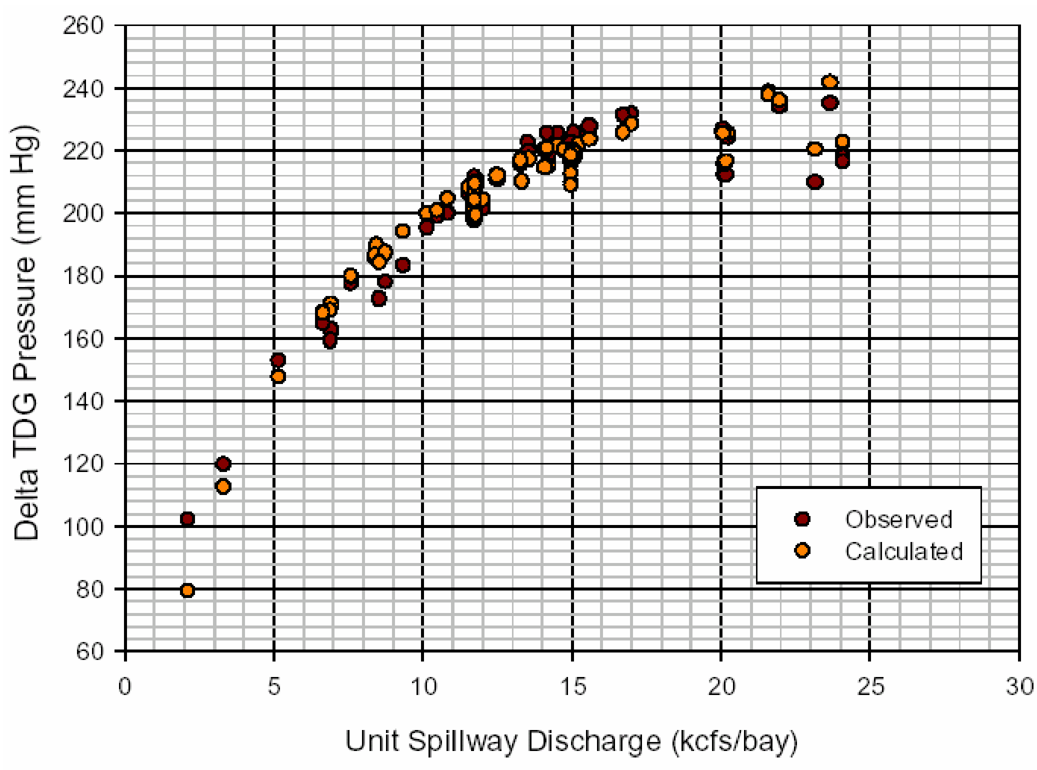

Figure 18. Unit Spillway Discharge versus TDG Pressure Above Barometric Pressure at Lower Monumental Dam, Juvenile Spill Pattern, 1997.

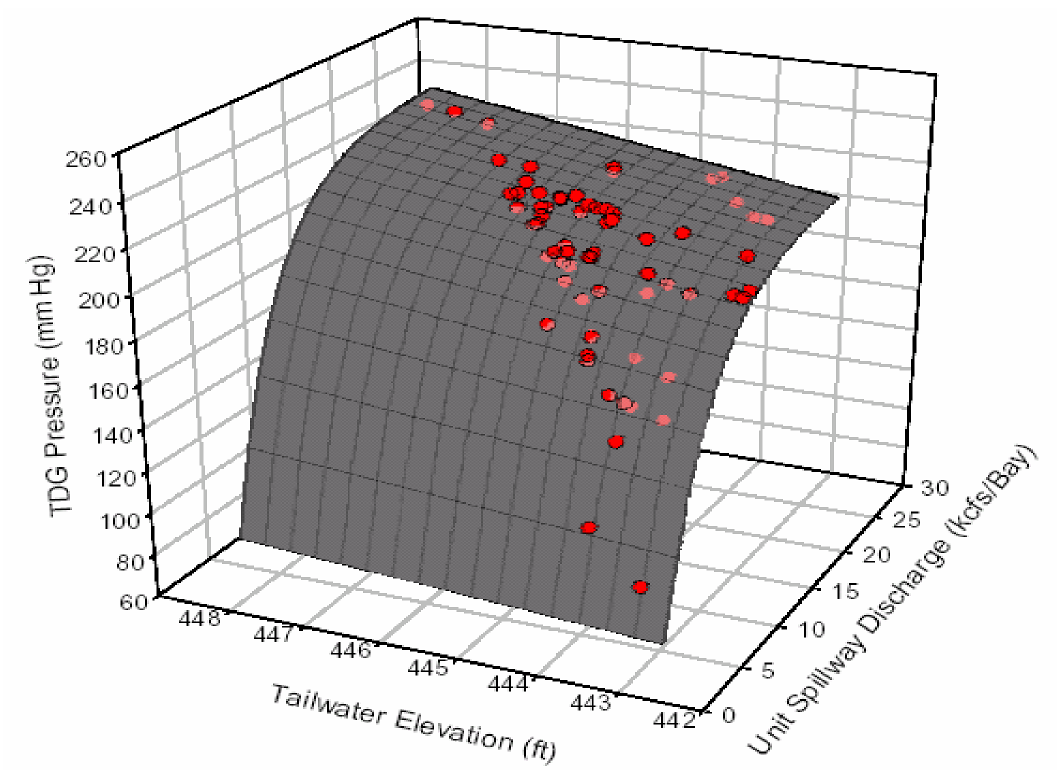

Figure 19. Unit Spillway Discharge, Tailwater Elevation, and TDG Pressure Above Barometric Pressure at Lower Monumental Dam, 1997.

The response function as defined in Equation 14 was used to create a hindcast of the TDG production observed during the 1997 spill season. The hourly project operation and TDG saturation at the Lower Monumental FMS's (LMN-forebay, LMNW-tailwater) for the month of May 1997 are shown in Figure 20 along with the estimates of TDG saturation based on Equation 14. In general, the estimated tailwater TDG saturation (LMNW-cal) was generally within 1 percentage point of the observed tailwater TDG saturation. Spillway releases greater than 40 kcfs generally produced tailwater TDG saturation greater than 120 percent during this period. Forced spillway releases of 120 kcfs generated tailwater TDG saturation in excess of 132 percent. The usage of the adult spill pattern in Figure 20 is indicated by the operation of spillway bay 1 (QS1-red).

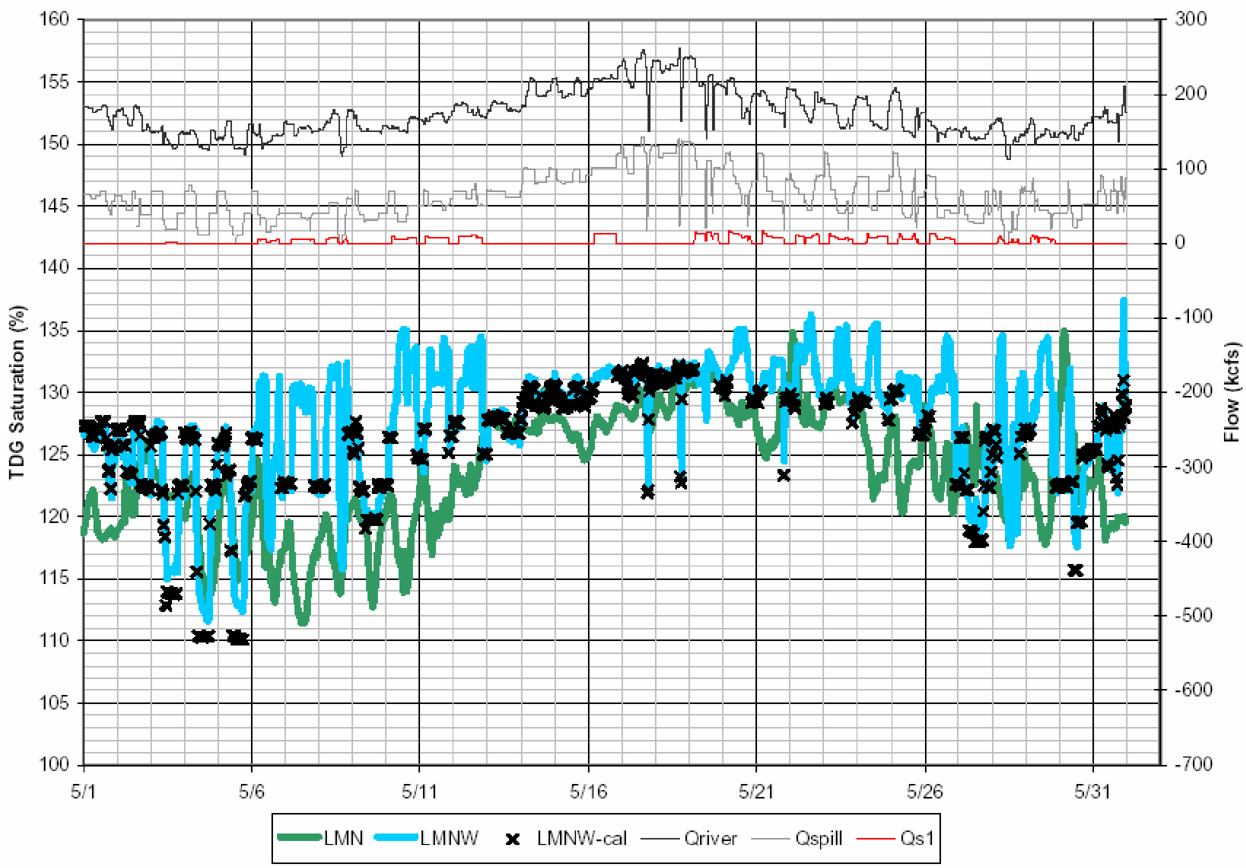

Figure 20. Observed and Estimated TDG Saturation at the Tailwater Fixed Monitoring Station at Lower Monumental Dam, May 1997.
(LMN=Observed Forebay TDG, LMNW=Observed Tailwater TDG, LMNW-cal =Calculated Tailwater TDG, QR=Hourly Total River Flow, QS=Hourly Spillway Flow)

The operations of all spillway bays in the adult spill pattern with a constant operation of 3 hours were identified during the 1997 spill season. This data filtering resulted in a total of only 34 independent hourly observations. The delta TDG pressure was found to range from 134.5 to 267.5 mm Hg as listed in Table 11. The range in unit spillway discharge was from 2.2 to 12.5 kcfs/bay and the tailwater depth ranged from 43.5 to 46.6 feet.

Table 11. Statistical Summary of Regression Variables

	Delta Pressure ΔP (mm Hg)	Unit Spillway Discharge q_s (kcfs/bay)	Tailwater Depth D_{tw} (ft)
Number	34	34	34
Minimum	134.5	2.2	43.5
Maximum	267.5	12.5	46.6
Average	237.1	7.5	45.1
Standard Deviation	23.8	2.5	0.8

Source: U.S. Army Corps of Engineers DGAS Study, Appendix G, p. G-23

The functional relationship for the TDG production of the adult spill pattern (Equation 15) was similar to the equation determined for spillway bays with flow deflectors at Lower Monumental. All of the coefficients determined by the nonlinear regression analysis were significant to the 99 percent confidence interval as shown in Table 12. This formulation contained a much higher standard error (15.9 mm Hg) than found in other production relationships with an r-squared of 0.57. The observed and calculated delta TDG pressures were plotted against the unit spillway discharge in Figure 21.

$$\Delta P = 5.427 D_{tw}(1 - e^{-0.580 q_s}) \qquad \text{Equation 15}$$

Table 12. Statistical Summary of Nonlinear Regression at Lower Monumental, Adult Spill Pattern, 1997 Spill Season

$$\Delta P_{tw} = c_1 * D_{tw} * (1 - \exp(c_2 * q_s))$$

Number of observations n=34

$r^2 = 0.57$

Std. Error = 15.9 mm Hg

Coefficient		Estimate from Regression	Standard Error	t-statistic	Probability
Deflectored bays	c_1	5.427	0.0853	63.5939	<0.0001
	c_2	-0.58	0.0769	7.5959	<0.0001

Source: U.S. Army Corps of Engineers DGAS Study, Appendix G, p. G-24

Entrainment of Powerhouse Discharge

Estimates of the entrainment of powerhouse flows into spillway discharge were not available from this near-field study because of the limited amount of powerhouse discharge. Visual observations of surface flow patterns below the powerhouse suggested that all powerhouse releases (14.5-19.2 kcfs) were being directed into the stilling basin. Since direct determination of the entrainment of powerhouse flows into the highly aerated conditions below Little Goose were not practical, it was assumed that the entrainment characteristics of Lower Monumental were similar to Ice Harbor. The estimates of the entrainment of powerhouse flows were estimated to average 30 kcfs and to be independent of the total spillway discharge.

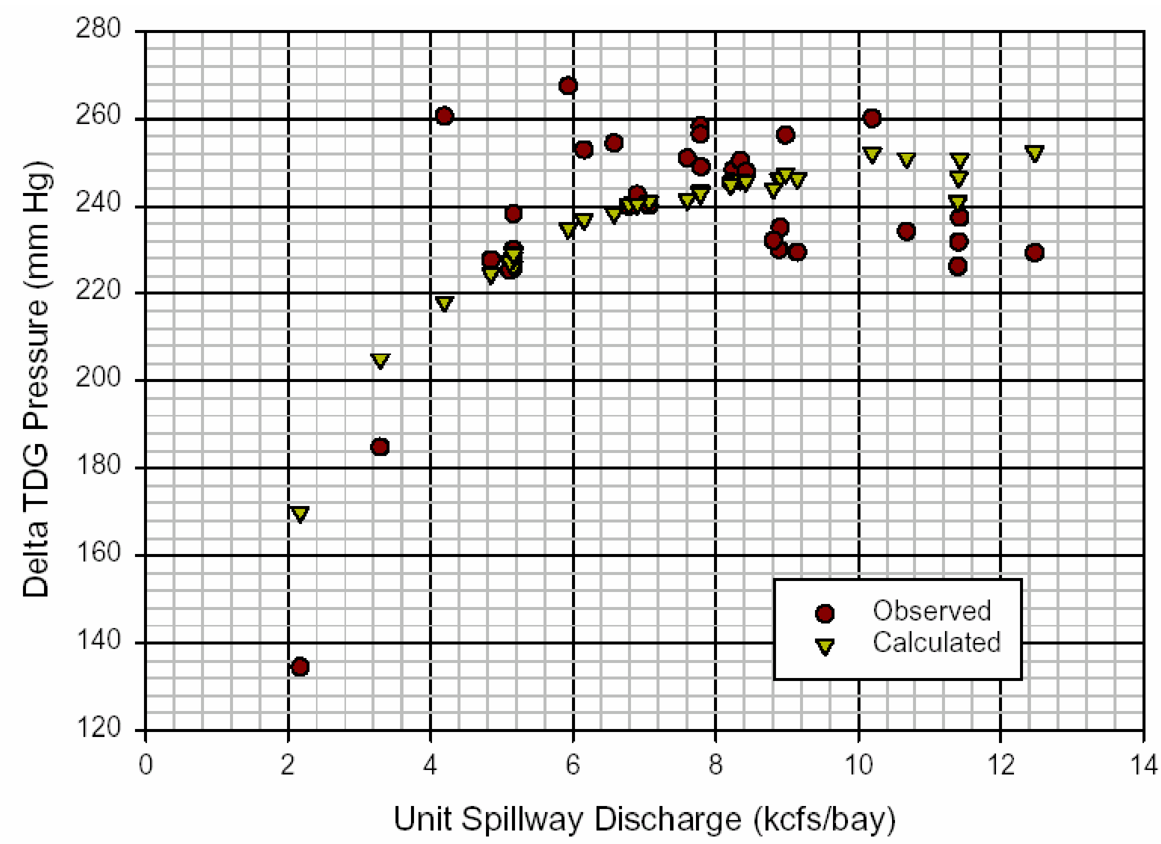

Figure 21. Unit Spillway Discharge versus TDG Pressure Above Barometric Pressure at Lower Monumental Dam, Adult Spill Pattern, 1997.

Ice Harbor Dam

TDG Exchange

The installation of spillway flow deflectors at Ice Harbor was completed in a staged schedule over 3 years. "Type II" flow deflectors were installed in spillway bays 2 through 9 at elevation 338 fmsl at Ice Harbor. The first four deflectors were completed during the winter of 1996-97 followed by four more deflectors in the fall of 1997. The end bay deflectors were completed during the winter of 1998-99.

The flow deflectors significantly changed the TDG exchange properties and spill management from Ice Harbor. A detailed post flow deflector near-field study of TDG exchange below Ice Harbor was conducted during March 5-9, 1998, as described by Wilhelms and Schneider (1998). The study consisted of sampling TDG pressures below the stilling basin during spillway discharges ranging from 15 to 75 kcfs with and without powerhouse flows. Several different spill patterns were investigated during this study: uniform bays 2 through 9 and standard spill pattern. The study findings indicated that the TDG production was directly related to the unit spillway discharge. The TDG saturation was found to be an exponential function of unit spillway discharge with 110 percent saturation associated with a unit spillway discharge of 3 kcfs/bay and 115 percent saturation generated for a unit spillway discharge of 8 kcfs/bay for the uniform spill pattern.

The data did support the additional influence of the tailwater depth of flow on the TDG exchange characteristics. The addition of flow deflectors significantly reduced the absorption of TDG in the stilling basin, reducing the peak TDG pressures just downstream of the stilling basin endsill from 170 to 135 percent saturation.

The evaluation of data from the tailwater FMS during 1998 provided the opportunity to study the TDG exchange of spillway flows under a wider range of operating conditions. The spillway operation at Ice Harbor was found to generate significantly lower TDG pressures during lower total river flow conditions in comparison to the other Snake River projects. The unit spillway discharge was plotted against the tailwater TDG saturation in Figure 22 for the filtered data during the 1998 spill season at Ice Harbor. Two distinct linearly related groupings of points, corresponding roughly with low and high total river flow conditions, can be seen in this figure. The lower limit of this data cluster corresponds with lower total river flows and low tailwater stage. The corresponding spill capacity for a 120 percent tailwater waiver standard can be as high as 100 kcfs based on the lower limit in this data cluster. The upper limit of this data cluster

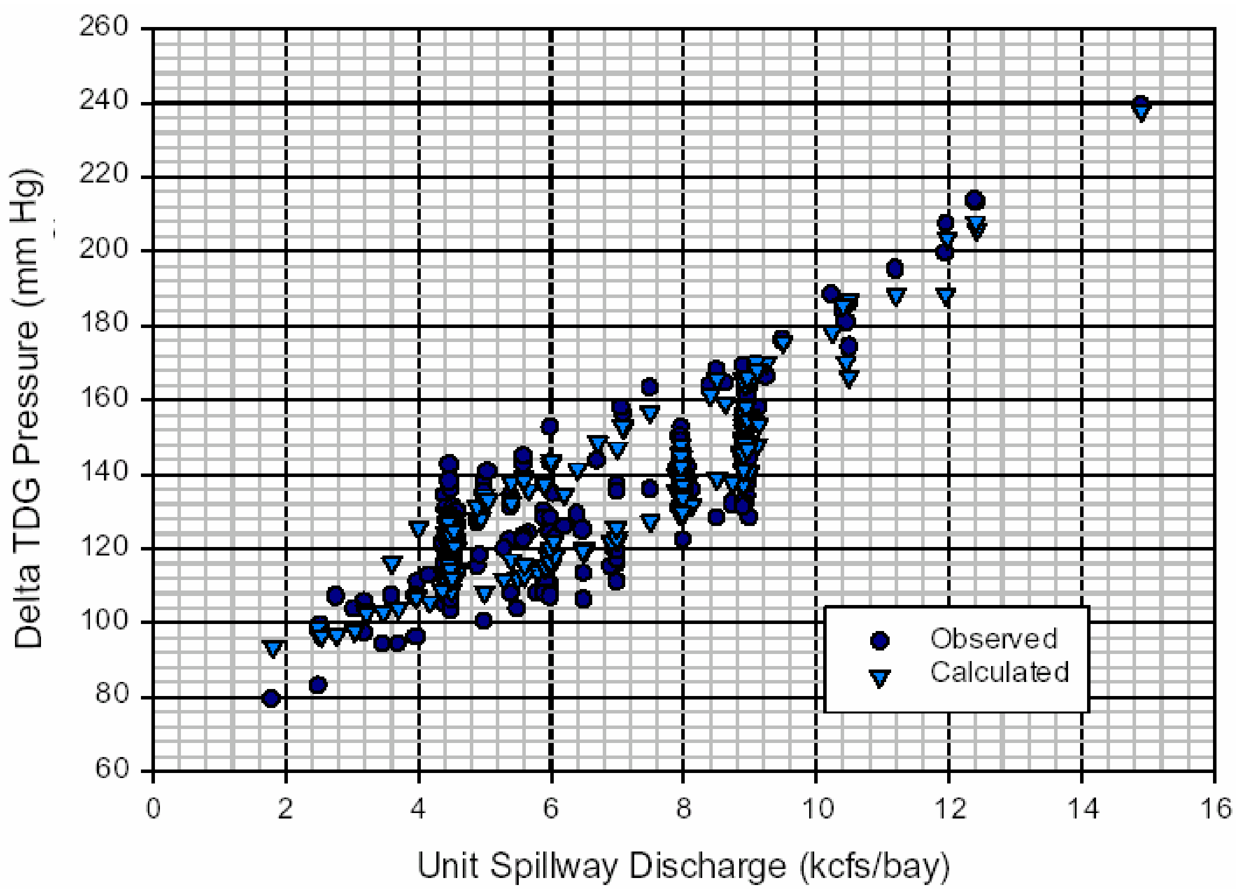

Figure 22. Unit Spillway Discharge versus TDG Pressure Above Barometric Pressure at Ice Harbor Dam, 1998.

corresponds with the highest total river flows experienced during 1998. The spill capacity for a TDG saturation of 120 percent in spillway releases into the tailrace channel could be as low as 70 kcfs. During the forced spill conditions at Ice Harbor (15 kcfs/bay discharges), the TDG pressures generated at Ice Harbor were significantly higher (10 to 20 mm Hg) than at upstream projects on the Snake River.

A second interesting feature of the relationship between unit spillway discharge and tailwater TDG saturation is the large variance in TDG saturation with unit spillway discharges of 4.5 and 9.0 kcfs/bay. These two spill levels correspond with the daytime and nighttime spillway capacities scheduled during much of the voluntary spring spill season. The data corresponding with a unit discharge of 9.0 kcfs/bay ±0.2 kcfs/bay were extracted from the body of the data and plotted against the tailwater stage, initial forebay saturation, and water temperature. The tailwater stage was found to be highly correlated with this subset of data for a constant unit spillway discharge. A linear regression between TDG saturation and tailwater stage resulted in a correlation coefficient of 0.76 and a slope of 0.8 percent saturation per foot. This relationship suggests an 8 percent increase in TDG saturation should result from a 10-foot increase in depth of the tailrace channel.

Regression

A nonlinear regression was performed on the data from the 1998 spill season. The dependent variable was TDG pressure above the barometric pressure at the tailwater FMS. The two independent variables were tailwater depth and average unit spillway discharge. To prevent the incorporation of redundant data pairs during the same extended operation, only data with a constant operation for 3 hours were included in the analysis, resulting in a sample set of 233 observations. The tailwater depth ranged from 19.4 feet to 34.5 feet, which corresponded with total river flows from 29.7 kcfs to 243 kcfs as listed in Table 13. The unit spillway discharge ranged from 1.8 to 14.9 kcfs/bay and the delta pressure ranged from 79.3 to 239.0 mm Hg.

Table 13. Statistical Summary of Regression Variables

	Delta Pressure ΔP (mm Hg)	Unit Spillway Discharge q_s (kcfs/bay)	Tailwater Depth D_{tw} (ft)
Number	234	234	234
Minimum	79.3	1.8	19.4
Maximum	239.0	14.9	34.5
Average	132.9	6.5	25.6
Standard Deviation	23.5	2.3	3.0

Source: U.S. Army Corps of Engineers DGAS Study, Appendix G, p. G-26

The change in TDG pressure, as defined by $\Delta P = P_{tw} - P_{bar}$, below Ice Harbor during spillway operations was found to be proportional to the product of tailwater depth and the specific discharge as shown in Equation 16. The regression equation was based on data collected during the 1998 spill season. All of the coefficients determined by the nonlinear regression analysis were significant to the 99 percent confidence interval as shown in Table 14. This formulation explained much of the variability in the estimated dependent variable with an r-squared of 0.90

and a standard error of 7.63 mm Hg. The constant coefficient of 84.57 forces a minimum TDG saturation of 112 percent at an atmospheric pressure of 755 mm Hg.

$$\Delta P = 0.014 D_{tw}^{2.097} q_s^{0.772} + 84.57 \qquad \text{Equation 16}$$

Where:

ΔP	=	$P_{tw} - P_{bar}$
P_{tw}	=	TDG pressure at the tailwater FMS (mm Hg)
P_{bar}	=	Barometric pressure at the tailwater FMS (mm Hg)
q_s	=	Flow-weighted unit spillway bay discharge (kcfs/bay)
D_{tw}	=	Tailrace channel depth (feet) (E_{tw}-E_{ch})
E_{tw}	=	Elevation of the tailwater (fmsl)
E_{ch}	=	Average elevation of the tailrace channel (500 fmsl)

Table 14. Statistical Summary of Nonlinear Regression at Ice Harbor, 1998 Spill Season

$\Delta P = c_1 * D_{tw}^{c2} q_s^{c3} + c_4$ Number of observations n=233 $r^2 = 0.90$ Std. Error=7.63 mm Hg				
Coefficient	Estimate from Regression	Standard Error	t-statistic	Probability
c_1	0.0140	0.0471	1.98	<0.0486
c_2	2.097	0.0652	11.66	<0.0001
c_3	0.772	0.1356	11.99	<0.0001
c_4	84.57	3.62	24.04	<0.0001

Source: U.S. Army Corps of Engineers DGAS Study, Appendix G, p. G-27

This relationship implies that both the depth of flow and specific discharge are important factors in determining the level of TDG exchanged during spillway releases. The response surface for TDG pressure above atmospheric pressure as a function of both unit discharge and tailwater stage is shown in Figure 23. The depth of the channel will influence the pressure time history of entrained air with larger depths resulting in a greater potential for the exchange of TDG. The specific discharge or discharge per spillway bay reflects the amount of energy available during spillway releases, which will establish the turbulence and the potential to entrain air in the stilling basin. The level of forebay TDG saturation was not an important parameter. Water temperature was not a significant variable in the exchange relationship at Ice Harbor.

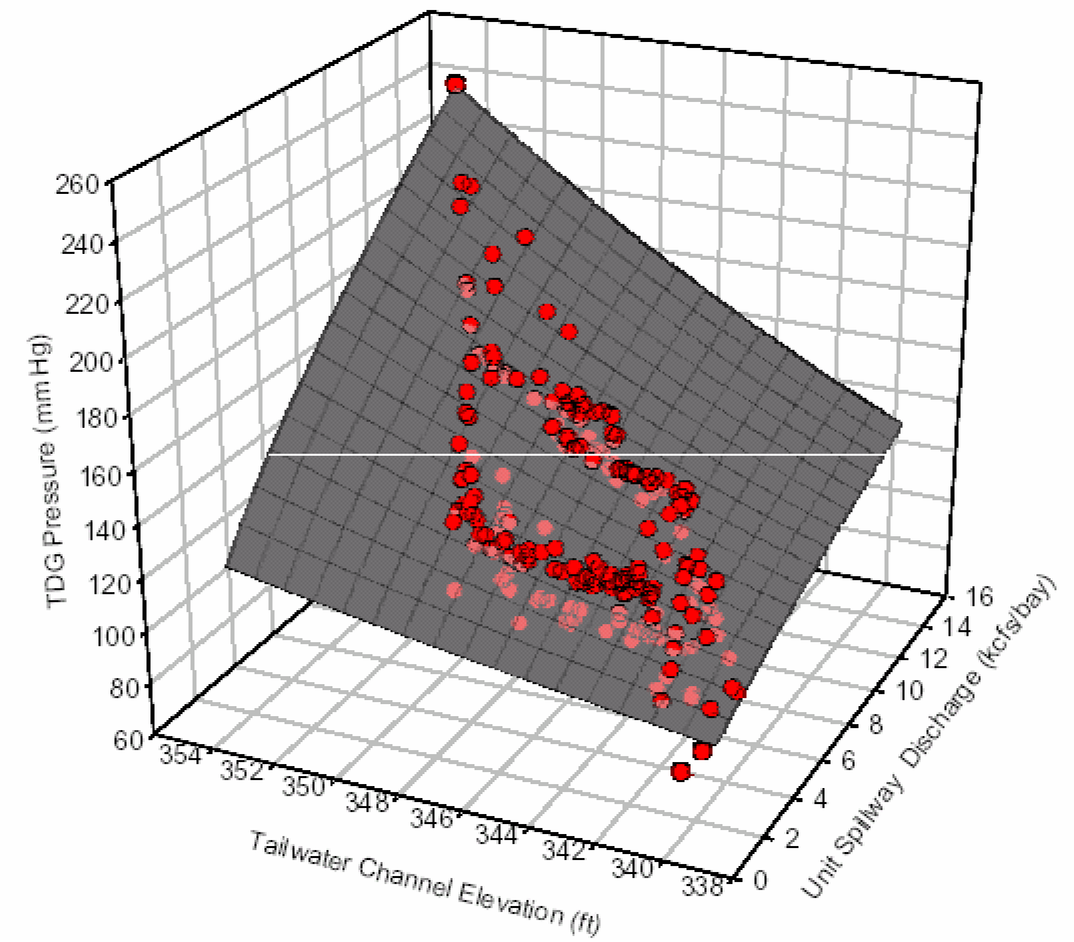

Figure 23. Unit Spillway Discharge, Tailwater Elevation, and TDG Pressure Above Barometric Pressure at Ice Harbor Dam, 1998.

Equation 16 was highly significant in explaining the variance in the TDG pressure at the tailwater FMS. The regression model was used to create a hindcast of the observed tailwater TDG saturation below Ice Harbor for the 1998 spill season. The results are shown in Figure 24 for the month of May 1998. The calculated TDG saturation closely tracked the diurnal variation in tailwater TDG saturation during May with a tendency to slightly overestimate the observed conditions during the beginning of the month. Even with this robust relationship, caution and judgment must be applied when using this equation outside the ranges of discharge and tailwater depth from which is was derived. The average, absolute, and root mean square error in TDG saturation computed using all of the observed data with spillway discharge during the months of April through July of 1998 were -0.3, 1.3, and 2.1 percent, respectively. The calculation of the error of estimate of the tailwater TDG pressure did not take into account the lagged time of response between operational changes and arrival of water at the tailwater FMS.

The management of project operations with regard to TDG must take into account the level of spillway discharge, spill pattern, and tailwater stage. The spill capacity resulting in 120 percent TDG saturation below Ice Harbor will be a direct function of both the total river flow, which is the determinant of tailwater stage, and unit spillway discharge.

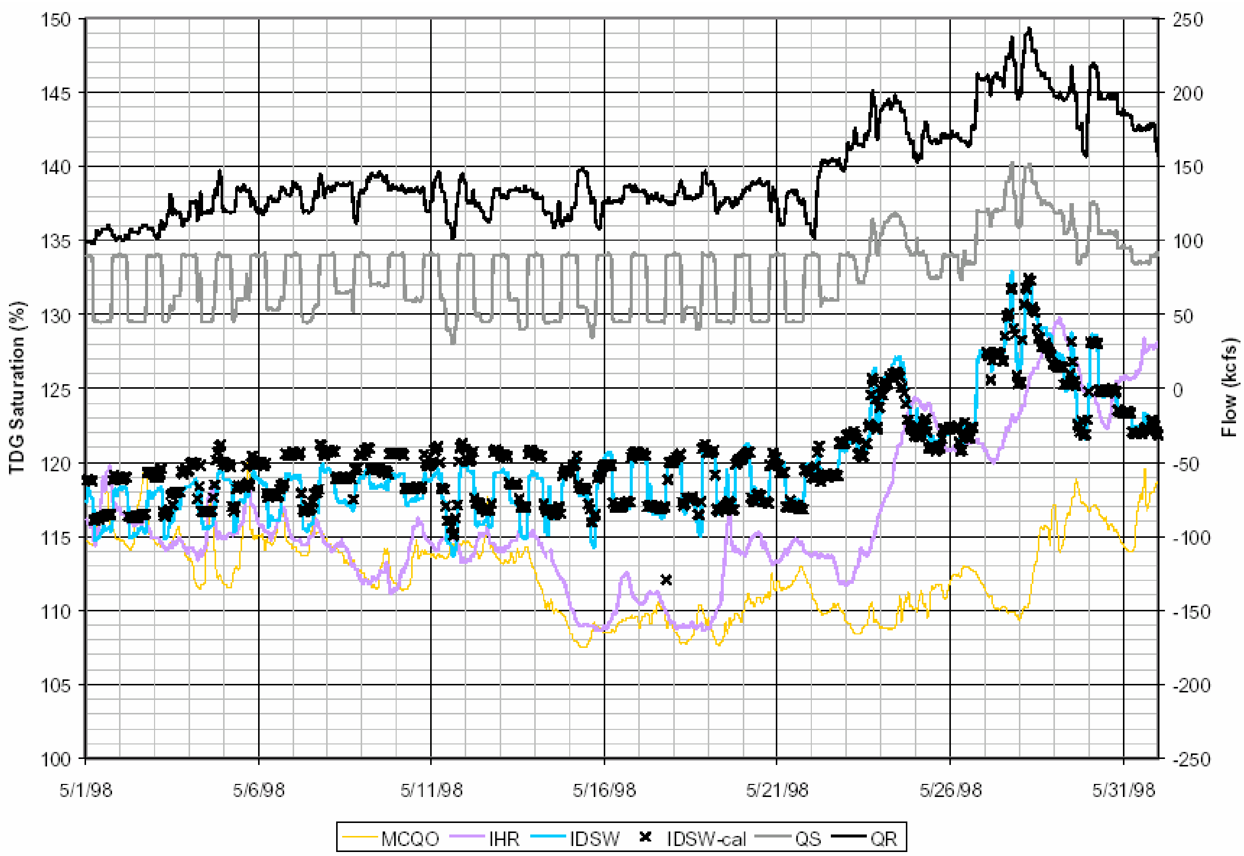

Figure 24. Observed and Estimated TDG Saturation at the Tailwater Fixed Monitoring Station at Ice Harbor Dam, May 1998.
(IHR=Observed Forebay TDG, IDSW=Observed Tailwater TDG, IDSW-cal =Calculated Tailwater TDG, QR=Hourly Total River Flow, QS=Hourly Spillway Flow)

Entrainment of Powerhouse Discharge

The entrainment of powerhouse flows into the highly aerated flow conditions below Ice Harbor was estimated from data collected during the 1998 spillway TDG exchange study. The powerhouse entrainment discharge was estimated for each flow condition by applying a simple mass balance statement of powerhouse and spillway project flows. The estimates of the entrainment of powerhouse flows were found to range from 26.4 to 38.5 kcfs and average about 30 kcfs. The powerhouse entrainment discharge was not found to vary as a function of the total spillway discharge.

Loading Capacity

Linkage of TDG Loading to the Criteria

As discussed above, the fundamental process that elevates TDG is gas transfer between the air and water at the boundary of entrained bubbles, driven by differential gas pressures. For any given spill volume and tailwater depth, the excess pressure over ambient barometric pressure, ΔP, can be predicted. The mass loading of air that is associated with any given ΔP will depend on water temperature. However this mass loading is of less importance than ΔP, since it is ΔP that drives whether gas bubble trauma will occur. For these reasons, using excess pressure rather than mass loading to express loading capacity is appropriate for this TMDL, and is supported by the Clean Water Act's allowance for the use of "other appropriate measures" in the development of TMDLs.

To determine the TMDL loading capacity, ΔP can be directly related to the TDG water quality criteria, as describe in Equation 6:

$$S_{tdg} = \frac{(P_{atm} + \Delta P)}{P_{atm}} * 100$$

If S_{tdg} is set at the criterion of 110 percent saturation, the equation can be rearranged to establish a ΔP loading capacity (ΔP_{lc}):

$$\Delta P_{lc} = P_{atm} * 0.1$$

To choose a critical barometric pressure P_{atm} for establishing a loading capacity, the 95th percentile low pressure was determined. Data from the FMS sites on the Snake River from 1995 through 2002 were evaluated, and the 95th percentile low barometric pressure ranges from 736 mm Hg at the Lower Granite forebay to 746 mm Hg in the Ice Harbor Tailrace. Therefore, the loading capacity for the Lower Snake River is set to ΔP of 74 mm Hg.

Load and Wasteload Allocations

For the purpose of this TMDL, each dam will be provided with a load allocation, because no NPDES permits will be issued to the dams to regulate TDG caused by spills[2]. This approach is also reasonable for several reasons:

- Spills entrain air to reach a polluted state, much like a high-energy release of water might erode a stream bank.
- Dams are essentially very large instream structures that will require modifications to achieve compliance with water quality standards.
- The level of improvement expected from any specific structural or operational modification is uncertain, and therefore a series of modifications may be needed to achieve the desired outcome, with effectiveness monitoring to assess results.

Wasteload allocations in this TMDL are zero, because there are no NPDES-permitted point sources that contribute to elevated TDG in the Lower Snake River.

A possible source of TDG to the Lower Snake River is Palouse Falls, located on the Palouse River several miles upstream of the Lower Monumental pool. Research has shown that natural water falls may increase TDG, such as several studies have shown for Kootenai Falls in Montana. TDG and flow data were analyzed to determine the potential effect of Palouse Falls on the Lower Snake River. Back-calculations of TDG in the Palouse River suggest that TDG levels over 110% are possible during high flow events. However, the analysis also suggests that the potential increase in TDG from the Palouse River is negligible, because flows in the Palouse River are usually a small fraction of Snake River flows (commonly 2-4% during high flows, and rarely over 5%). Detailed monitoring and modeling is needed to determine the influence of Palouse Falls with certainty. However, this analysis is sufficient to determine that a load allocation for the Palouse River is unnecessary.

Table 15 shows the load allocations for each of the four dams and pools on the Lower Snake River. Because of the unique nature of TDG, load allocations are not directly expressed in terms of mass loading. Like loading capacity, allocations are in terms of ΔP. Load allocations for the September through February season are equal to loading capacity at each dam's spill and at the upstream boundary, and zero for each pool. The load allocation for Ice Harbor Dam is based on the allocation at the upstream boundary of the Lower Columbia River TDG TMDL (Pickett and Harding, 2002).

Load allocations during March through August for spills at the three upstream dams and for the upstream boundary are lower than loading capacity because loading capacity is split between the LA for the downstream pool and the LA for the upstream spill or boundary. Each pool LA

[2] The Courts have determined the characterization of dams as point sources for which NPDES permits will not be issued for certain parameters. The current policy of the State of Washington is to not issue NPDES permits for TDG.

represents an increase in TDG percent saturation caused when ambient water temperatures increase as water moves downstream through the pool of the downstream dam. This occurs

Table 15. Load Allocations for TDG in Lower Snake River

Location Name	Load Allocation (as ΔP , excess pressure above ambient, mm Hg)	
	March-August	September-February
Upstream Boundary (Idaho border)	60	74
Lower Granite Pool – temperature change	14	0
Lower Granite Dam spill	53	74
Little Goose Pool – temperature change	21	0
Little Goose Dam spill	61	74
Lower Monumental Pool – temperature change	13	0
Lower Monumental Dam spill	62	74
Ice Harbor Pool – temperature change	12	0
Ice Harbor Dam spill	75	75

because, if gas exchange is negligible (such as occurs on windless days) an increase in water temperature will decrease the saturation concentration. As a result, a fixed mass of TDG in the pool will represent a higher TDG percent saturation if water temperature increases.

To determine the pool LAs, the potential temperature increase in each pool was evaluated. For each dam the time of travel was estimated from the application of EPA's RBM-10 model (USEPA, 2001) for a 30-year period. The 90th percentile travel time (in days) was determined for each month. FMS data were then evaluated to determine the maximum temperature increase for each day during the travel time for the appropriate month. The load allocation for each pool equals the increase in TDG caused by the median temperature increase during the spill season.

However, it is possible that windy conditions in the TMDL cause sufficient degassing to offset increases in TDG from water temperature increases. Average daily wind speed was evaluated and plotted against temperature increases (shown in Figures 25 and 26 for Lower Granite and Ice Harbor pools). Then the potential degassing effect was evaluated from several of the equations used in TDG modeling as summarized in Appendix B of Cole and Wells (2001). This analysis indicates that increasing temperature generally occurs during periods of low wind with low rates of degassing. Therefore, the effect of water temperature increases on TDG is included in this TMDL without including the effect of wind.

Given the clear mathematical relationship between spill quantities, the load allocations (ΔP), and TDG percent saturation, compliance with load allocations will be met by specifying operational and structural goals for spills that prevent the load allocation from being exceeded. In general, the long-term goal of meeting water quality standards must be met with structural modifications to the dam projects. In the short-term, operational methods will be used to protect beneficial uses to the fullest extent and meet standards whenever possible.

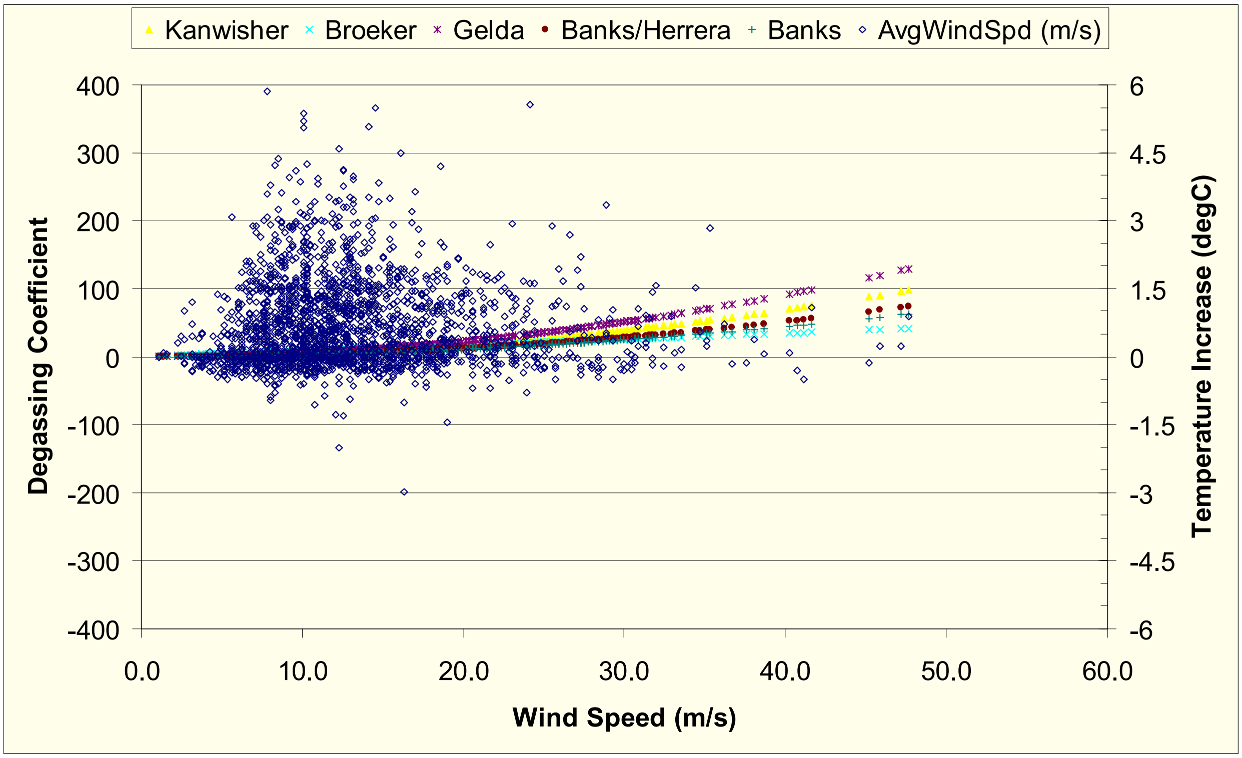

Figure 25. Comparison of Water Temperature Increases to Wind Speed at Lower Granite Dam.

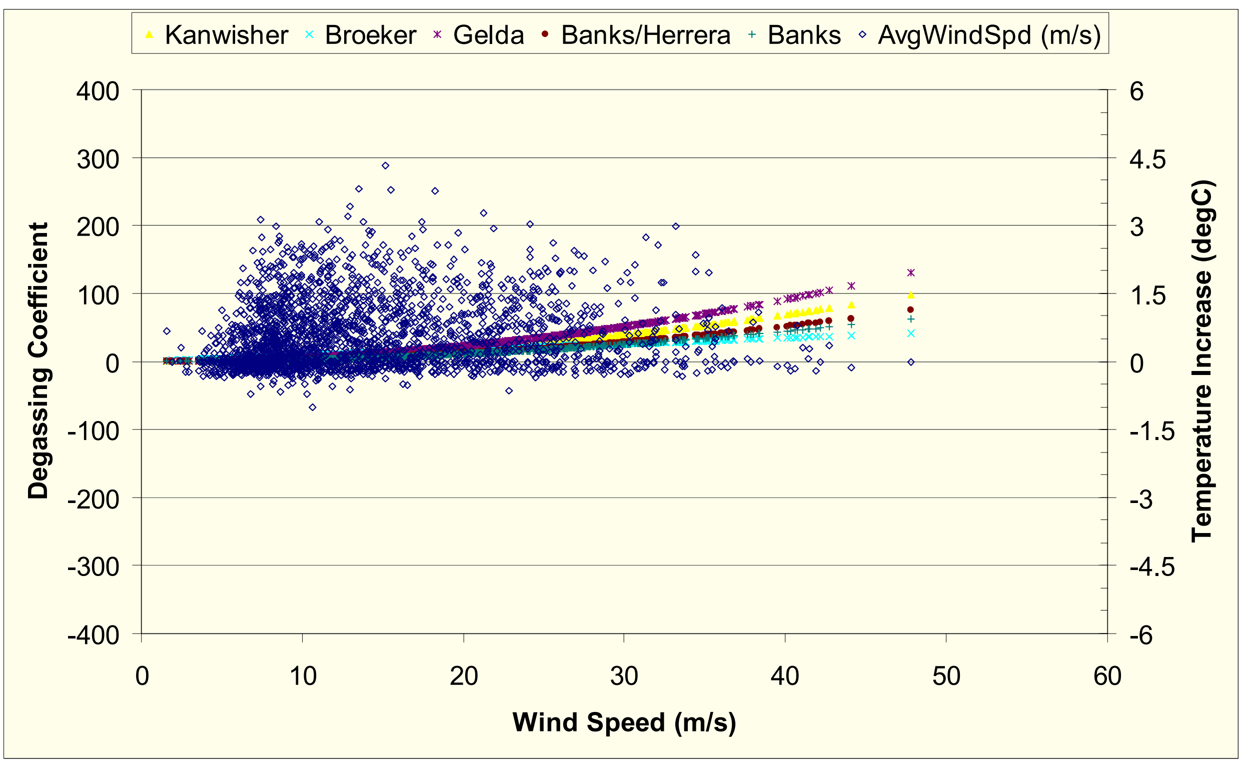

Figure 26. Comparison of Water Temperature Increases to Wind Speed at Ice Harbor Dam.

Long-term Compliance with Water Quality Standards

Compliance with Standards for All Spills

Federal and state laws and rules require compliance with state water quality standards, and therefore the ultimate goal of this TMDL is to achieve compliance. However, to meet this goal, this TMDL must address several complicating factors.

In much of the literature a distinction is made between "voluntary" and "involuntary" spill. In terms of compliance with water quality standards, this distinction is misleading. Endangered Species Act requirements for spills must be considered to be just as binding as Clean Water Act requirements. And like many other situations in the environmental field, the solution for a problem impacting one resource may cause problems to another resource.

As an example, chlorine may be added to wastewater to provide disinfection to protect public health. But chlorine can also create a problem with toxicity in the effluent for fish and other beneficial species. This conflict does not mean dischargers stop disinfecting; they either need to reduce chlorine toxicity by dechlorination or find other non-chlorine methods of disinfection. The goal here is to balance two valued resources, human health and aquatic life.

Similarly, the dams have an obligation to both meet water quality standards and Endangered Species Act requirements. If spills are necessary to protect endangered species, then those spills must also meet standards to protect aquatic life in general. The dam operators also have the option of finding alternative ways to protect species without spills.

The point is that spills for fish passage are not really "voluntary"; rather they are spills required for reasons other than a lack of powerhouse capacity. If the public interest necessitates that spills be required to protect fisheries or other beneficial uses of the water, then dams must meet water quality standards under spills of any volume up to the 7Q10 flood flows. In addition, spills can occur at any time and at any volume due to lack of power demand or powerhouse maintenance or failure. Therefore, this TMDL will be applicable for all spills below 7Q10 river flood flow conditions, regardless of the cause of the spill. (*Seasonal Variations* below discusses 7Q10 flows.)

Operational versus Structural Solutions

The Lower Snake River dams, as currently designed, are incapable of meeting the water quality standards for all spill flow levels below 7Q10 flood conditions. Therefore, compliance with this TMDL will require structural changes. The Dissolved Gas Abatement Study (DGAS) report outlines a variety of alternatives for operational and structural changes, which move in the direction of compliance under all spill levels. However, the effectiveness of these changes can only be estimated, and must be assessed after implementation. Also, implementation of structural solutions is dependent on Congressional appropriations. Therefore long-term compliance with this TMDL will take a significant length of time and must take into account a certain level of inherent uncertainty.

Compliance Locations

The compliance locations for dam spills were chosen from several options, illustrated in Figure 27:

1. By a strict interpretation of state water quality standards without any consideration of applying the mixing zone provisions of the water quality standards, the point of compliance would be at the point of maximum TDG. However this is a location that is difficult to identify and monitor in real time, and does not take into account the rapid degassing in the aerated zone.

2. If mixing zone provisions were applied to the aerated zone (the area of bubble entrainment and dissipation), then the point of compliance would be at the end of the aerated zone. This location would be easier to identify for regulatory purposes.

3. The point of compliance could be at the tailwater FMS sites, but mixing zone provisions would need to be applied to the entire river, including powerhouse flow. The locations of the tailwater FMS sites are clearly identified. However, they are inconsistent with respect to the amount of mixing they represent between water gassed by the spill and water unchanged from the forebay.

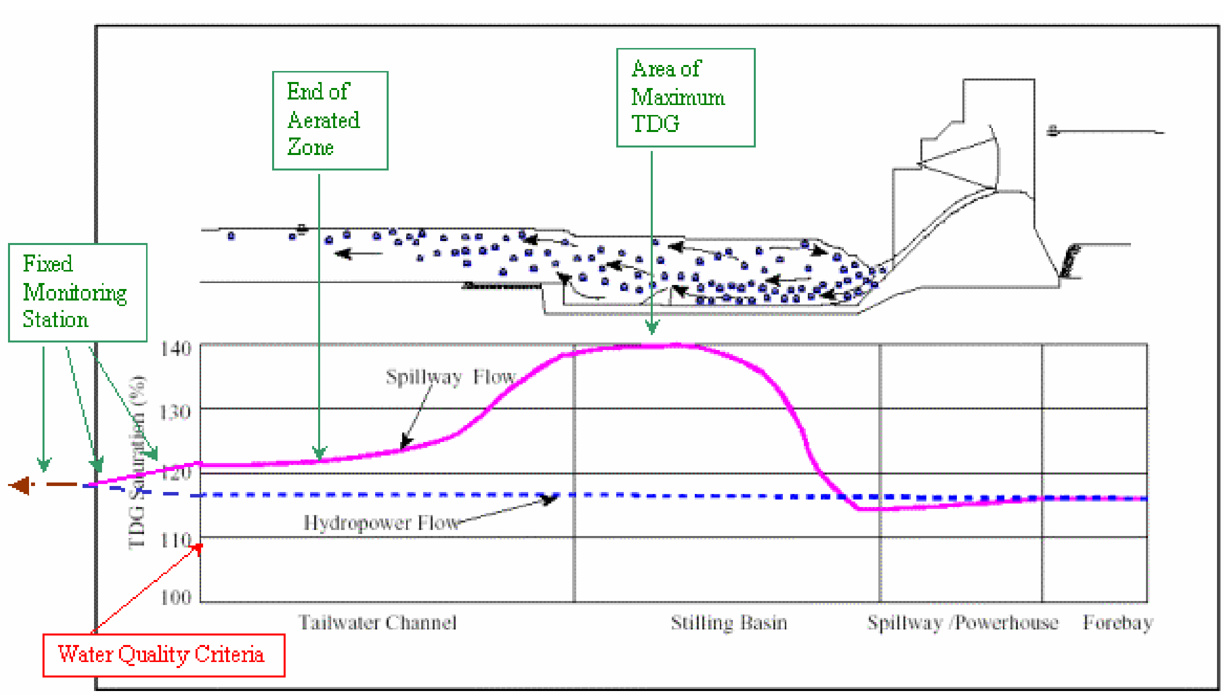

Figure 27. Possible locations of Compliance Locations with Respect to TDG Levels.

The point of compliance for load allocations for the dams in this TMDL will be based on application of the mixing zone to the aerated zone immediately below the spillways of the dams. The water quality standards for the state of Washington provide an allowance for a mixing zone, and compliance with standards is required at the boundary of the mixing zone. There are several reasons that use of a mixing zone is appropriate in this situation:

- TDG levels rise immediately below the spillway, but then degas for some distance downstream. The points of compliance were determined from U.S. Army Corps of Engineers research which identified the location where degassing was mostly complete. This is a local area of impact with very dynamic conditions.
- Because the area below the spillway is very dynamic, TDG levels are difficult to accurately assess.
- Extensive fisheries research has shown that most anadromous fish are able to pass through this area below the spillway quickly without ill effects.
- Because of the turbulent flow associated with the spill above the compensation depth (the depth where hydrostatic pressure equals ΔP), little or no resident fish habitat is available in this area. The zone below the compensation depth is by definition in compliance with standards.
- Provision of a mixing zone and deviation from the size requirements are appropriate because of the public interest in ensuring that water quality standards are applied appropriately to the dam projects.

The compliance locations for load allocations are shown in Table 16. The load allocation for the upstream boundary applies at the Idaho border, and will be addressed by the State of Idaho under EPA oversight. The compliance location for each spill load allocation will be at the end of the aeration zone in the tailrace of each dam, at the location specified in the Table 16. The pool above each dam must comply with the appropriate load allocation at all locations in the pool, although the primary compliance location is the forebay at the downstream end of the pool.

Table 16. Compliance Locations for TDG Load Allocations

Project	Location
Upstream Boundary	Lower Granite Pool Below Idaho Border
Lower Granite Dam spill	1500 feet below end of spillway [1]
Little Goose Dam spill	1500 feet below end of spillway [2]
Lower Monumental Dam spill	1200 feet below end of spillway [3]
Ice Harbor Dam spill	1300 feet below end of spillway [4]

[1]Pickett, 2002
[2]Schneider and Wilhelms, 1998a
[3]Schneider and Wilhelms, 1996
[4]Wilhelms and Schneider, 1998

Monitoring of Compliance

For monitoring of long-term compliance in the spills, it will be necessary to monitor at the load allocation compliance locations in the tailrace. However, it is not expected that these locations will lend themselves to a permanent remote monitoring setup. Compliance will be determined by a combination of periodic synoptic surveys, especially after structural changes have been completed, and continuous monitoring, using a statistical relationship between the continuous monitor and conditions at the compliance location. This allows long-term monitoring to be managed separately from monitoring for short-term operational needs.

For short-term compliance, the FMS stations can continue to be used, or new FMS stations can be established. This will allow operational management that is linked to easily accessible data, based on overall environmental management needs and the realities imposed by structural characteristics. Thus, short-term compliance can remain adaptive and flexible, while long-term compliance remains fixed to firm goals.

No monitoring station currently exists to assess compliance at the upstream boundary. Existing information should be reviewed to determine the best method to assess compliance with Washington's TDG standards at the state line, which could then be included in the Detailed Implementation Plan.

Compliance with allocations in the pools will be assessed both by comparison of FMS tailrace and downstream forebay monitoring, and by detailed synoptic surveys. Since the allocations are based on historical temperature regimes, detailed monitoring will be most appropriate following changes in temperature management procedures that alter typical temperature increases, such as through implementation of a temperature TMDL or ESA requirements.

Margin of Safety

The margin of safety for this TMDL is implicit in the TMDL analysis through the use of conservative assumptions. A detailed analysis of how the margin of safety is included is provided below.

Critical Conditions

No specific high- or low-flow critical conditions exist for this TMDL. Spills that generate high gas levels can occur in any season and load allocations are applicable to spills at all flow levels below the 7Q10 flood flow.

Certain parameters that are necessary to develop load allocations were established at levels equivalent to critical conditions. As described above, time of travel, temperature, and barometric pressure were all developed at critical levels. This approach introduces several conservative assumptions that provide a margin of safety to the TMDL, especially considering the low probability of these critical conditions occurring at the same time. In addition, the exclusion of the effect of wind in reducing gas levels has introduced an additional margin of safety.

Criteria versus Site-specific Conditions

Probably few river systems have been as extensively studied for the effects of TDG than the Columbia/Snake system. Extensive research has been conducted for over 40 years on TDG and aquatic life. Federal, state, and tribal fishery agencies all support a more lenient standard than currently in state regulation. Review of EPA guidance also suggests the criterion could be applied with an averaging period, rather than as an instantaneous value. Therefore, the current standards include an implicit margin of safety when applied to this river system.

Data Quality and Quantity

A margin of safety is usually identified in a TMDL to recognize uncertainty in the data used to produce the TMDL. Due to the monitoring requirements imposed by the Washington State Department of Ecology as a part of the fish passage program over the past seven years, there is a great deal of hourly data of TDG levels, barometric pressure, water temperature, tailwater elevation, forebay elevation, total river flow and spill quantity. Fairly rigorous standardized data quality procedures are provided for this data. These data are available on the Technical Management Team homepage, hosted by the Northwest Division of the U.S. Army Corps of Engineers at:
http://www.nwd-wc.usace.army.mil/TMT/welcome.html.

Further, the Corps has undertaken an extensive Dissolved Gas Abatement Study (DGAS) over the past five years. The study included near-field TDG monitoring and the development of a mathematical model to describe the production, dissipation, and behavior of TDG in the

Columbia system for the federal projects. The data collection also followed standardized data quality procedures. The production of TDG at the four hydroelectric projects that are the identified sources in this TMDL are, therefore, well understood.

As a result of this monitoring there is abundant data of good quality for constructing this TMDL. Therefore, the margin of safety required for data and modeling variability in this TMDL can be relatively small.

Seasonal Variation

In the lower Snake River, exceedances of the TDG standard occur during the months of March through August, which cover both the fish out-migration season and the high-flow season in conjunction with spring runoff. One of the determinants of TDG levels is total river flow. When river levels are particularly high, TDG levels rise more rapidly if there is any water spilled over the spillway. During low-flow periods, there is generally not a TDG problem, other than spill for fish passage, as long as all water is passed through the powerhouses.

Occasionally turbine units will be out of service for maintenance, either scheduled, or on an emergency basis. This may require water to be spilled, because there are insufficient turbines available to handle the water in the river. This can occur due to Bonneville Power Administration power purchasing and the sequencing of water releases from upstream storage reservoirs.

Clearly, there is little control over emergency outages. Maintenance is generally scheduled (1) to coincide with low electricity demand periods, and (2) when river flows are such that they will not cause TDG exceedances.

In summary, spills can occur at any time, although they are most likely in the spring and early summer. This TMDL will apply during the entire year, with separate allocations for the March through August season (when temperature changes in the pool can affect TDG levels) and for the September through February season (for involuntary spill outside the runoff season).

7Q10 Flows

As discussed above, Washington's water quality standards only apply when river flows are below the 7Q10 flood flows. The Snake River 7Q10 flow was calculated from flows measured and reported by the U.S. Geological Survey (Snake River below Ice Harbor Dam, Station No. 13353000). Methodology followed the guidelines of the U.S. Water Resources Council (1981).

Annual peak 7-day average flows were calculated (using the October-September Water Year from 1975 through 2000), and then the 10-year return flow was determined by the Log-Pearson Type 3 method. The skew coefficient used in the analysis was calculated from the data; the generalized and weighted skew was not determined or used, but the error introduced by this shortcut was probably small to nil.

The 7Q10 flood flow calculated for the Snake River is 214 kcfs. This applies throughout the TMDL area, because no tributaries enter the Snake River large enough to alter peak flows. Flows in the Palouse River were subtracted to determine the 7Q10 flood flow above the Palouse River, and the same result was obtained. An earlier calculation of 7Q10 by the Corps was slightly higher because flows for years prior to the construction of Dworshak Dam were included in the calculation. Dworshak has likely reduced peak flood flows due to its operation for flood storage.

Summary Implementation Strategy

Overview

The goal of this total dissolved gas TMDL for the Lower Snake River is to meet Washington's water quality standards for TDG. The goal of water quality standards is to protect beneficial uses of the river. While these include such beneficial uses as hydropower generation, irrigation, drinking water, and water contact recreation, the most sensitive use is anadromous salmonids. These species are particularly vulnerable, as they navigate past the dams both as downstream migrating juveniles and as upstream returning adults.

The four dams on the river pass water by spilling over the spillway, by generating electricity through the turbines, and to a much lesser extent by passing water through special fish facilities such as adult ladders and juvenile fish passageways. TDG is generated by spilling water over the spillway. Absent considerations for fish survival, spills are considered "involuntary" since they occur due to lack of powerhouse capacity. Involuntary spills can be caused by flood flows, lack of electric load for powerhouse generation, or turbines being off-line due to maintenance or repair. However, fish survival needs necessitate spills to improve juvenile fish passage.

Up to a point, the danger to fish from exposure to high TDG is overshadowed by the dangers to fish of going through the turbines. In response, the National Marine Fisheries Service performed a comparison risk analysis that forms the basis for modifications to Washington's water quality standard for TDG.

In December 2000, the National Marine Fisheries Service released a Biological Opinion under the federal Endangered Species Act for 12 listed species in the Columbia and Snake Rivers. A significant component of this Biological Opinion is the provision of spilled water at the Lower Snake River hydropower facilities to facilitate fish passage. In addition, spill for juvenile fish passage is beneficial for non-ESA listed species. Clearly, if spilled water is the cause of elevated TDG levels but is required for fish passage, care needs to be taken not to implement gas abatement measures that may benefit water quality, while damaging the beneficial uses, such as juvenile migration, that the federal Clean Water Act was designed to protect.

This implementation strategy therefore must take into account both requirements: to reduce high TDG generated at the dams by spilling water, and to provide the levels of spill under the Biological Opinion to facilitate fish passage. Additional provision for spill is sometimes necessary for non-listed species.

Gas reduction at the four Lower Snake River dams has been the subject of intensive research over the past six years. Federal fish agencies, tribes, the U.S. Environmental Protection Agency, Bonneville Power Administration, state fish and wildlife departments, and the U.S. Army Corps of Engineers are organized into work groups to address the TDG problems. The result of this is a much enhanced understanding of the generation and dynamics of TDG production. In addition, implementation actions designed to reduce TDG generation have already been undertaken (e.g., the installation of flow deflectors or "flip lips" at Ice Harbor Dam). Further actions are planned, but funding is often dependent on Congressional approval and is linked to basin priorities for the Snake River.

Implementation Plan Development

The operation of the Columbia River hydropower system is carried out through multiple agencies and governed by several regulatory authorities. The following is a list of these parties:

- The U.S. Army Corps of Engineers operates the dams and provides engineering, contracting and construction authorities (based on funding from Congress) for structural changes at these dams. The Corps provides flood control oversight and responds to the energy, environmental, transportation, and recreational needs of the public. The Corps is required to achieve a balance between these requirements where they conflict.

- The National Marine Fisheries Service and the U.S. Fish and Wildlife Service oversee the protection of endangered species, four of which are anadromous salmonids found in the Lower Snake River. Several forums have been established to oversee implementation of the Biological Opinion requirements for these species. These forums include the Water Quality Team, who focuses on temperature and TDG management, the Technical Management Team that makes decisions regarding hydropower operations, the System Configuration Team that makes decisions on structural modifications, and an implementation or policy team to which policy issues that cannot be resolved in the other forums are elevated.

- Tribes have treaty rights to the salmon in the Snake River and are involved on many levels of fish management and environmental protection.

- The Bonneville Power Administration oversees power production and distribution. Revenues help fund fish and environmental mitigation for the impact of the dams.

- Washington Department of Fish & Wildlife works within the forums detailed above, as well as protects and enhances non-listed salmon, resident fish, and wildlife.

- The U.S. Environmental Protection Agency is part of the caucus of federal agencies involved in operation and management of the federal Columbia River hydropower system. Its specific role is to ensure consistency with federal environmental laws and regulations. The agency will ultimately approve this TMDL under Section 303(d) of the federal Clean Water Act.

- Washington State's Department of Ecology will oversee implementation of this TDG TMDL. They will work collaboratively with the U.S. Army Corps of Engineers, Bonneville Power Administration, tribal, and other state and federal agencies through existing forums. Tools available include interagency agreements, administrative orders, and gas abatement approvals required by surface water quality standards. Review of gas abatement requirements will be done primarily through the Corps' Water Quality Plan for the Columbia and Snake Rivers. Other forums such as the ESA Fish Facility and Design Review Work Groups, the Technical Management Team, Water Quality Team, and the Structural Configuration Team will also be involved as needed.

- Numerous other agencies are involved in different aspects of river management that can have a bearing on TDG generation. The most prominent include the Northwest Power Planning Council, data gatherers such as the Fish Passage Center and U.S. Geological Survey, and the upriver states of Idaho and Oregon.

Meeting the load allocations in this TMDL will fall into two phases. Phase I will involve improving water quality, while ensuring that salmonid passage is fully protected in accordance with the National Marine Fisheries Service's Biological Opinion. Phase II will involve structural and operational changes to dams to achieve the water quality standard for TDG.

The short-term actions in Phase I will focus on meeting the fish passage performance standards as outlined in the National Marine Fisheries Service 2000 Federal Columbia River Power System Biological Opinion through spills that generate gas no greater than the "waiver" levels of the water quality TDG standards (Washington temporary special conditions). Water quality standards are measured at existing fixed monitoring stations managed by the U.S. Army of Engineers. This phase will also include short-term structural modifications at the dams to achieve TDG reductions during periods of spill, while ensuring that the fish passage requirements of the 2000 Biological Opinion are met. As part of Phase II, a Detailed Implementation Plan or equivalent will be developed (possibly through the Water Quality Plan under the Biological Opinion).

Phase II will evaluate success from the short-term actions. The second phase will also move toward further structural modifications and reductions in fish passage spill if the Biological Opinion specified performance standards are being met and adequate survival is provided for non-listed species.

Biological monitoring has been required by the state of Washington in order to assess gas bubble trauma to fish as a result of spill. Based on six years of data, the results show little trauma to migrating juvenile salmon at TDG levels allowed by the states in their modified water quality standards. As a result, thought has been given to permanently modifying the water quality standards or establishing site-specific criteria for TDG for the Snake River. The purpose of this TMDL, however, is to allocate loads to meet the existing water quality standard.

Changing water quality standards is a separate process and is not one of this TMDL's implementation strategies. However, the authors of this report support the evaluation of the appropriateness of the water quality standards for these four specific sites on the river in terms of TDG impacts to aquatic species. Any revision would proceed through the normal scientific review of the standard to ensure full beneficial use protection. The Water Quality Team could be a resource to support this effort.

Implementation Activities

As the operator of the four Lower Snake River dams, the U.S. Army Corps of Engineers published its Final Draft Technical Report and Appendices of the Phase II Dissolved Gas Abatement Study (DGAS) in April 2001. This study was undertaken as part of the Columbia

River Fish Mitigation Program. This study has been the result of an ongoing collaborative effort between many federal and state fisheries agencies, dam operators, tribes, and environmental agencies toward reducing TDG in the river in balance with enhancing spill opportunities for juvenile salmon.

As detailed above, this implementation strategy is to be carried out in two phases.

Short Term – Phase I

This phase is already underway, as a result of actions taken by the Corps, and will continue through 2010. As detailed above, the emphasis in this phase will be taking those actions that will result in reductions of TDG, while ensuring the fish passage requirements of the 2000 Biological Opinion are met. The Biological Opinion envisions spill for fish passage under modified water quality standards of Washington, as have been provided for the past six years. Included in this program will be the near-term actions that have been identified in the Biological Opinion. Maintenance of required spill at the modified standards to allow for fish passage will be as measured at the fixed monitoring stations both in the forebay and the tailrace of each dam.

This phase will also address the first stages of reducing gas during spills due to high-flow events, turbine outages, and during lack of demand for electrical power. This is outlined in the Corps report, "Final Draft Dissolved Gas Abatement Report," April 2001.

Table 17 includes specific mainstem Snake River structural implementation actions (from the National Marine Fisheries Service 2000 Federal Columbia River Power System Biological Opinion) that have been completed or will be completed during this phase and are directly related to achievement of the water quality standard.

Table 17. Short-term Implementation Activities

2000 Biological Opinion Action Item Description	Completion Date	Action Item #
Ice Harbor Deflectors	Done	134
Survival based spill caps at all dams	Ongoing	68, 82
Lower Monumental Endbay Deflectors	Done	134
Little Goose Endbay Deflectors	2005	134
Divider Walls at Appropriate Dams	Under Evaluation	135

Several operational implementation actions are available to minimize involuntary spill that are already in use, or can be evaluated during Phase I and implemented if practical. These include:

- Scheduling routine turbine maintenance and repair during low-power load and river flow periods.
- Preventive maintenance of turbines to prevent breakdown.

- System management of water release from upstream storage reservoirs to minimize involuntary spills at dams in the TMDL area.
- Optimizing power purchasing to allow maximum use of powerhouse capacity and minimization of involuntary spill.

Specific implementation methods for these actions will be provided in a Detailed Implementation Plan (DIP), or equivalent. The gas abatement plan provided by the Corps to Ecology and Ecology's conditions of approval will provide details for the DIP. The state and the Corps are working together to coordinate gas abatement plans and the DIP with the Water Quality Plan, which is being developed by the Corps to meet (among other things) dissolved gas standards in the Snake River.

Table 18 contains additional short-term implementation actions that are indirectly related to achievement of the water quality standard. Implementation of these measures, though, is likely to improve salmonid passage and help achieve the performance standards of the Biological Opinion. Carrying out these actions will enable a decreased reliance on spilling water for fish passage in the near-term period. Voluntary spill levels for fish passage with their associated TDG will be reduced as these actions are implemented, and will result in achieving the survival performance standards contained in the 2000 Biological Opinion.

Table 18. Additional Short-term Implementation Activities

2000 Biological Opinion Action Item Description	Completion Date	Action Item #
Lower Granite Removable Spillway Weir	Done	80
Lower Monumental Bypass Outfall Relocation	2004 or 2005	76

Long Term – Phase II

This phase will begin in 2011 and proceed through 2020. Actions taken in the previous phase will be reviewed for their efficacy, both in improving TDG levels and for protecting salmonid passage. The Biological Opinion survival goals are being met through fish passage actions other than spilling water. Reductions in gas entrainment through spill will be realized so that the required final goal of meeting the water quality standard for TDG can be met as measured at the end of the aerated zone below each dam.

Table 19 details those long-term actions that will protect fish passage while moving the system toward attainment of the water quality standard for TDG.

The U.S. Army Corps of Engineers DGAS study identified a number of structural measures designed to abate TDG. Several of these measures should be evaluated for their efficacy in abating gas and ensuring that they provide safe and effective fish passage. If necessary, those measures found to be effective and safe should be identified for funding and implementation.

Table 19. Fish Passage Actions That Support TDG Water Quality Goals

2000 Biological Opinion Action Item Description	Completion Date	Action Item #
Removable Spillway Weirs at Lower Monumental, Little Goose, and Ice Harbor	Under Evaluation	75, 77
Lower Monumental Extended Screens	Under Evaluation	78
Spill Effectiveness Studies	Ongoing	83
Predator Removal and Abatement	Ongoing	100-103
Improved Operation and Maintenance	Ongoing	58,59,63,144, 145,146
Implement Turbine Survival Program Results	Under Evaluation	88, 90, 91, 92

Reasonable Assurance

In support of this implementation strategy, structural work has already been carried out to reduce high levels of TDG at the four Lower Snake River dams. The track record for Congressional funding for these projects is good and there is reason to believe that further funding of projects will continue. Funding for the more expensive structural modifications of the second phase is entirely dependent on Congressional will, national and regional priorities, and budgetary availability of funds. Funding to improve fish passage facilities also has a good track record, and there is reason to believe that this will continue to be funded both through Congress and energy revenues.

Ecology has regulatory authority over the four federal dam projects. Washington's regulatory authority comes through the *Federal Clean Water Act*, the *Revised Code of Washington's Pollution Control Act 98-48* and the *Washington Administrative Code's Water Quality Standards 173-201A*.

The Washington State Department of Ecology is responsible for ensuring that water quality standards are met. Ecology is confident that the collaborative relationship with the dam operators toward reducing gas will continue and be enhanced through this TMDL. The U.S. Army Corps of Engineers has agreed to continue working through the Endangered Species Act forums established to oversee and to carry out the requirements of the Biological Opinion.

Special dissolved gas conditions exist in the Washington State Water Quality Standards for the Snake River. Higher gas levels are allowed in these standards in order to pass juvenile salmonids in spill and avoid the turbines in the Snake River. However, the dam owner has to provide assurances that they are taking steps to reduce dissolved gasses in order to get an 'approval' for this special condition from Department of Ecology. The Corps must submit a gas abatement plan to Ecology for approval. Ecology's approval will include certain conditions.

Monitoring, compliance schedules and reporting is required. This standard can be found in Washington State Water Quality Standards 173 201A (060) (4).

Adaptive Management

The process for reviewing the status of implementation of this TMDL will follow the timing and process for the review of the federal Biological Opinion in 2010. The Washington State Department of Ecology will convene an advisory group comprising representatives of tribes and federal and state agencies to evaluate appropriate points of compliance for this TMDL. Based on these findings, further studies may be needed, and structural and operational gas abatement activities will be redirected or accelerated if needed.

Monitoring Strategy

Short-term compliance and the effectiveness of operational implementation actions will be monitored at existing fixed monitoring station sites. The current fixed monitoring station TDG monitoring system consists of tailrace and forebay monitoring stations at each mainstem lower Snake River dam and at key locations in some tributaries. While these stations do a credible job of reporting meaningful data, some at times may not be achieving desired sampling objectives (representing spill or average forebay conditions).

This system is now undergoing a thorough review by the National Marine Fishery Service's Water Quality Team. Screening criteria have been developed and are used to evaluate all existing monitoring stations. Stations that do not conform to these criteria will be relocated to more appropriate locations. This screening process will include consideration of how well the station represents TDG and water temperature in a given river reach and how sensitive the station is to non-spill factors that affect TDG, such as temperature and aquatic plant respiration.

Monitoring of long-term compliance with load allocations and the effect of structural changes will include an evaluation of previous and future near-field transect studies at the compliance location (the end of the aerated zone below each dam). Load allocation compliance monitoring will occur following major structural changes or immediately following the end of Phase I and Phase II. Also, statistical relationships may be developed between TDG levels at the continuous monitoring location and the compliance location that allow real-time and long-term trend evaluation of compliance.

Prior to the initiation of a load allocation monitoring survey, a quality assurance project plan, or equivalent, must be approved by the Washington State Department of Ecology. The quality assurance project plan should address the safety and stability of the site to support monitoring equipment and activities when subject to the strong hydraulics below the dams. Due to these factors, it is possible that an alternate site may be needed. If so, some correlation to the load allocation compliance point will be necessary.

Potential Funding Sources

A discussion on funding is warranted, given the expensive nature of some of the suggested structural actions. Known funding sources include power generation revenues through Bonneville Power Administration, as directed by the Northwest Power Planning Council and System Configuration Team and the U.S. Congress.

Summary of Public Involvement

The state of Washington developed and implemented the Public Involvement and Outreach strategy for this TMDL project in partnership with the Columbia and Snake Rivers Mainstem TMDL Coordination Team. Team members include US Environmental Protection Agency, Idaho Department of Environmental Quality, Oregon Department of Environmental Quality, Washington State Department of Ecology, Western Governors Association, Columbia Basin Tribes, and the Columbia River Inter-Tribal Fish Commission.

The public involvement period on this proposed TMDL began ________ and ended _______.

Public hearings were held:

- _______

Individual outreach meetings were held with the appropriate watershed advisory groups and with primary stakeholders, which included:

- Nez Perce Tribe
- Umatilla Tribe
- U.S. Army Corps of Engineers (Portland, Walla Walla, and Seattle Districts, and Pacific Northwest Division)
- Bonneville Power Administration
- National Marine Fisheries Service

In addition, meetings and presentations were held with the National Marine Fisheries Service Water Quality Team that includes federal and state agencies, public utility districts, tribes, and Bonneville Power.

The TMDL team held public meetings to receive input and comments from all interested participants. These meetings included public workshops to accept informal comments for each regional phase of the TMDL project, and public hearings for the formal public comment period.

The TMDL team used public outreach tools such as letters, focus sheets, and other printed materials; websites with short narratives and graphics, downloadable documents and relevant links; news releases and special news articles; and field visits.

Public Involvement Actions

- U.S. Environmental Protection Agency website
- Focus sheets
- News releases
- E water news – Washington State University Water Research Center newsletter article

- Monthly coordination team meetings – EPA, Idaho Department of Environmental Quality, Oregon Department of Environmental Quality, Washington State Department of Ecology, Western Governors Association, Columbia Basin Tribes, Columbia River Inter-Tribal Fish Commission (CRITFC)
- Monthly updates and discussions with the NMFS Water Quality Team
- Presentations to the NMFS Implementation Team
- Public workshop in Portland, OR – Nov. 28, 2000
- Columbia River Tribal TMDL workshop – Nov. 17 - 18, 2000
- Meeting with U.S. Army Corps of Engineers, U.S. Bureau of Reclamation, and Bonneville Power Administration – Jan. 30, 2001
- Public meetings in Spokane, WA and Portland, OR – July 23 - 24, 2001
- Presentations to CRITFC Tribal Water Quality Conference – Sept. 26 - 28, 2001
- Public meetings in Lewiston, Idaho and Pasco, WA – October 29 - 30, 2001
- Meetings with U.S. Army Corps of Engineers and U.S. Bureau of Reclamation – Nov. 5 & 15, 2001
- Meeting with CRITFC – Nov. 26, 2001
- Meeting with Washington Department of Fish and Wildlife – Dec. 11, 2001

References and Bibliography

Beeman, J.W., P.V. Haner, T.C. Robinson, and A.G. Maule, 1998. *Vertical and horizontal distribution of individual juvenile salmonids based on radio telemetry*. U.S. Geological Survey, Biological Resources Division, Columbia River Research Laboratory, Draft Report, Cook, Washington.

Beeman, J.W., T.C. Robinson, P.V. Haner, S.P. Vanderkooi, and A.G. Maule, 1999. *Gas bubble monitoring and research of juvenile salmonids*. Annual Progress Report of U.S. Geological Survey, Biological Resources Division, Columbia River Research Laboratory, Cook, Washington, to Bonneville Power Administration, Portland, Oregon.

Beiningan, K.T., and W J. Ebel, 1970. *Effect of John Day Dam on dissolved gas nitrogen concentrations and salmon in the Columbia River*, 1968. Transactions of the American Fisheries Society 99:664-671.

Blahm, T.H., R.J. McConnell, and G.R. Snyder, 1973. *Effect of gas supersaturated Columbia River water on survival of juvenile salmonids* April to June 1972. National Marine Fisheries Service, Prescott, Oregon.

Blahm, T.H., R.J. McConnell, and G.R. Snyder, 1975. *Effect of gas supersaturated Columbia River water on the survival of juvenile chinook and coho salmon*. U.S. Department of Commerce, National Marine Fisheries Service, NOAA Technical Report SSRF-688.

Blahm, T.H., R.J. McConnell, and G.R. Snyder, 1976. *Gas supersaturation research*, National Marine Services Prescott facility. Pages 11-19 *in* D. H. Fickeisen and M. J. Schneider, editors, Gas bubble disease. Technical Information Center, Energy Research and Development Administration, CONF-741033 Oak Ridge, Tennessee.

Bouck, G.R., A.V. Nebeker, and D.G. Stevens, 1976. *Mortality, saltwater adaptation and reproduction of fish exposed to gas supersaturated water*. U.S. Environmental Protection Agency, Office of Research and Development, EPA-600/3-76-050, Washington, D.C.

Cole, T.M. and S.A. Wells, 2001. *CE-QUAL-W2: A Two-Dimensional, Laterally Averaged, Hydrodynamic and Water Quality Model, Version 3.1, User Manual. I*nstruction Report EL-00-1, Environmental Laboratory, U.S. Army Corps of Engineers, Waterways Experiment Station, Vicksburg, MS.

Coutant, C.C., and R.G. Genoway, 1968. A*n exploratory study of interaction of increased temperature and nitrogen supersaturation on mortality of adult salmonids*. Final Report of Battelle Memorial Institute, Pacific Northwest Laboratory, Richland, Washington, to U.S. Bureau of Commercial Fisheries.

Dawley, E.M., T. Blahm, G. Snyder, and W. Ebel, 1975. S*tudies on effects of supersaturation of dissolved gases on fish*. National Marine Fisheries Service, Northwest Fisheries Science Center, Seattle, Washington.

Dawley, E.M., and W.J. Ebel, 1975. E*ffects of various concentrations of dissolved atmospheric gas on juvenile chinook salmon and steelhead trout*. Fisheries Bulletin 73(4):787-796.

Ebel, W.J., 1969. *Supersaturation of nitrogen in the Columbia River and its effect on salmon and steelhead trout*. National Marine Fisheries Bulletin 68:1-11.

Ebel, W.J., 1971. D*issolved nitrogen concentration in the Columbia and Snakes rivers in 1970 and their effect on chinook salmon and steelhead trout*. National Marine Fisheries Service Special Scientific Report 646:1-7.

Ebel, W.J., H.L. Raymond, G.E. Monan, W.E. Farr, and G.K. Tanonaka, 1975. E*ffect of atmospheric gas supersaturation caused by dams on salmon and steelhead trout of the Snake and Columbia Rivers*. National Marine Fisheries Service, Northwest Fisheries Science Center, Seattle, Washington.

Elston, R., J. Colt, P. Frelier, M. Mayberry, and W. Maslen, 1997. *Differential diagnosis of gasemboli in the gills of steelhead and other salmonid fishes*. Journal of Aquatic Animal Health 9:259-264.

Elston, R., J. Colt, S. Abernethy, and W. Maslen, 1997. *Gas bubble reabsorption in Chinook salmon: pressurization effects*. Journal of Aquatic Animal Health 9(4):317-321.

Gray, R.H., and J.M. Haynes, 1977. D*epth distribution of adult chinook salmon (Oncorhynchus tshawytscha) in relation to season and gas supersaturated water*. Transactions of the American Fisheries Society 106(6):617-620.

Hans, K.M., M.G. Mesa, and A.G. Maule, 1999. *Rate of disappearance of gas bubble trauma signs in juvenile salmonids*. Journal of Aquatic Animal Health 11:383-389.

ISAB, 1999. *Review of the National Marine Fisheries Service draft cumulative risk analysis addendum "An assessment of lower Snake River hydrosystem alternatives on survival and recovery of Snake River salmonids."* Independent Scientific Advisory Board, Report 99-6, for Northwest Power Planning Council, Portland, Oregon. October 12.

Jensen, J.O.T., J. Schnute, and D.F. Alderdice, 1986. *Assessing juvenile salmonid response to gas supersaturation and ancillary factors*. Canadian Journal of Fisheries and Aquatic Sciences 501.

Knittel, M.D., G.A. Chapman, and R.R. Chapman, 1980. *Effects of hydrostatic pressure on steelhead in air supersaturated water*. Transactions of the American Fisheries Society 109:755-759.

Maule, A. G., J. Beeman, K. M. Hans, M. G. Mesa, P. Haner, and J. J. Warren, 1997. *Gas bubble disease monitoring and research of juvenile salmonids*. U.S. Department of Energy, Bonneville Power Administration, Annual Report 1996 (Project 96-021), Portland, Oregon.

Maule, A.G., M.G. Mesa, K.M. Hans, J.J. Warren, and M.P. Swihart, 1997. *Gas bubble trauma monitoring and research of juvenile salmonids*. U.S. Department of Energy, Bonneville Power Administration, Environment, Fish and Wildlife, Annual Report 1995 (Project 87-401), Portland, Oregon.

Meekin, T.K., and R.L. Allen, 1974. S*ummer chinook and sockeye salmon mortality in the upper Columbia River and its relationship to nitrogen supersaturation*. Nitrogen supersaturation investigations in the mid-Columbia. Washington Department of Fisheries, Technical Report 12:127-153, Olympia, Washington.

Meekin, T.K., and B.K. Turner, 1974. *Tolerance of salmonid eggs, juveniles, and squawfish to supersaturated nitrogen*. Washington Department of Fisheries, Technical Report 12:78-126, Olympia, Washington.

Mesa, M.G., L.K. Weiland, and A.G. Maule, 1999. *Progression and severity of gas bubble trauma in juvenile salmonids*. Transactions of the American Fisheries Society 129:174-185.

Muir, W.D., S.G. Smith, J.G. Williams, and B.P. Stanford, in review. *Survival of PIT-tagged juvenile salmonids passing through bypass systems, turbines, and spillways and with and without flow deflectors at Snake River dams*. National Marine Fisheries Service, Northwest Fisheries Science Center, Seattle, Washington.

Nebeker, A.V., J.D. Andros, J.K. McCardy, and D.G. Stevens, 1978. *Survival of steelehead trout (Salmo gairdneri) eggs, embryos, and fry in air-supersaturated water*. Journal of the Fisheries Research Board of Canada 35:216-264.

Nebeker, A.V., D.G. Stevens, and R.K. Stroud, 1976. E*ffects of air-supersaturated water onadult sockeye salmon (Oncorhychus nerka)*. Journal of the Fisheries Research Board of Canada 33:2629-2633.

NMFS, 1996. *1995 annual report to Oregon Department of Environmental Quality*. National Marine Fisheries Service, Portland, Oregon.

NMFS, 1997. *1996 Annual report to Oregon Department of Environmental Quality*. National Marine Fisheries Service, Portland, Oregon.

NMFS, 1998. *Oregon Department of Environmental Quality 1997 Annual Report*. National Marine Fisheries Service, Portland, Oregon.

NMFS, 1999. *1998 annual report to Oregon Department of Environmental Quality*. National Marine Fisheries Service, Portland, Oregon.

NMFS, 2000a. *1999 annual report to Oregon Department of Environmental Quality*. National Marine Fisheries Service, Portland, Oregon.

NMFS, 2000b. *White paper: passage of juvenile and adult salmonids past Columbia and Snake River dams*. National Marine Fisheries Service, Northwest Fisheries Center, Seattle, Washington.

NMFS, 2000c. *White paper: predation on salmonids relative to the Federal Columbia River Power System*. National Marine Fisheries Service, Northwest Fisheries Center, Seattle, Washington.

NMFS, 2000d. *White paper: salmonid travel time and survival related to flow in the Columbia basin*. National Marine Fisheries Service, Northwest Fisheries Center, Seattle, Washington.

NMFS, 2000e. *White paper: summary of research related to transportation of juvenile anadromous salmonids around Snake and Columbia River dams*. National Marine Fisheries Service, Northwest Fisheries Center, Seattle, Washington. April.

NMFS, 2000f. E*ndangered Species Act - Section 7 Consultation, Biological Opinion: Reinitiation of Consultation on Operation of the Federal Columbia River Power System,* *Including the Juvenile Fish Transportation Program, and 19 Bureau of Reclamation Projects in the Columbia Basin.* National Marine Fisheries Service, Northwest Region Office, Seattle, Washington.

Orlins, J.J. and J.S. Gulliver, 2000. D*issolved Gas Supersaturation Downstream of (sic) a Spillway, Part II: Computational Model*. Journal of Hydraulic Research, 38 (2), 151-159.

Pickett, P.J., 2002. T*otal Dissolved Gas Monitoring Results, Columbia and Snake Rivers, May-July 2002.* Draft Report, Environmental Assessment Section, Washington Department of Ecology, Olympia, WA.

Pickett, P.J. and R. Harding, 2002. Total Maximum Daily Load for Lower Columbia River Total Dissolved Gas. Washington State Department of Ecology Publication No. 02-03-004. Prepared jointly by the Oregon Department of Environmental Quality and the Washington State Department of Ecology, Portland, OR and Olympia, WA.

Raymond, H.L., 1969. E*ffect of John Day Reservoir on the migration rate of juvenile Chinook salmon and steelhead from the Snake River, 1966 to 1975*. Transactions of the American Fisheries Society 98:513-514.

Raymond, H.L., 1979. E*ffects of dams and impoundments on migration of juvenile Chinook salmon and steelhead from the Snake River, 1966-1975*. Transactions of the American Fisheries Society 109:505-509.

Raymond, H.L., 1988. E*ffects of hydroelectric development and fisheries enhancement on spring and summer chinook salmon and steelhead in the Columbia River Basin*. North American. Journal of Fish Management 8:1-24.

Rowe, W.D., 1997. A*n anatomy of risk*. Wiley, New York.

Ryan, B.A,. and E.M. Dawley, 1998. E*ffects of dissolved gas supersaturation on fish residing in the Snake and Columbia Rivers, 1997*. National Marine Fisheries Service, Fish Ecology Division, Northwest Fisheries Science Center, Seattle, Washington, to Bonneville Power Administration (Project 96-022-00).

Ryan, B.A., E.M. Dawley, and R.A. Nelson, 2000. M*odeling the effects of dissolved gas supersaturation on resident aquatic biota in the mainstem Snake and Columbia rivers*. North American Journal of Fish Management 20:180-192.

Schneider, M.J. 2001, Personal communication. Water Quality Advisor, National Marine Fisheries Service, Portland, Oregon.

Schneider, M.L. 1996. T*otal Dissolved Gas Data Documentation and Preliminary Analysis: Near-Field Study of the Ice Harbor Tailwater*, CEWES-HS-L Memorandum for Record dated 13 June 1996. U.S. Army Waterways Experiment Station, Vicksburg, Mississippi.

Schneider, M.L. 2002. P*ersonal Communication*. Coastal and Hydraulics Laboratory, Engineer Research and Development Center, US Army Corps of Engineers, The Dalles, OR.

Schneider, M.L. and S. Wilhelms. 1996. N*ear-Field Study of TDG in the Lower Monumental Spillway Tailwater*, CEWES-CS-L Memorandum for Record dated 6 December 1996. U.S. Army Waterways Experiment Station, Vicksburg, Mississippi.

Schneider, M.L. and S. Wilhelms. 1997. D*ocumentation and Analysis of the Near-Field Ice Harbor Tailwater Study, June 27-28, 1996*,. CEWES-CS-L Memorandum for Record dated 27 January 1997. U.S. Army Waterways Experiment Station, Vicksburg, Mississippi.

Schneider, M.L. and S. Wilhelms. 1998a. *Total Dissolved Gas Exchange during Spillway Releases at Little Goose Dam, February 20-22, 1998*,.CEWES-HS-L Memorandum for Record dated 10 December 1998. U.S. Army Waterways Experiment Station, Vicksburg, Mississippi.

Schneider, M.L. and S. Wilhelms. 1998b .*Documentation and Analysis of the Ice Harbor Near-Field Tailwater Study, March 1998, Post-Deflector Installation,*. CEWES-HS-L Memorandum for Record dated 27 November 1998. U.S. Army Waterways Experiment Station, Vicksburg, Mississippi.

Schneider, M.L. and Wilhelms, S.C., 1998c. P*roposed Ice Harbor Raised Tailrace - Estimated TDG Saturation*, CEWES-CR-F Memorandum for Record dated 26 October 1998, U.S. Army Engineer Waterways Experiment Station.

Schoeneman. D.E., R.T. Pressey, and C.O. Junge Jr.,1961. Mortalities of Downstream Migrant Salmon at McNary Dam. Transactions of the American Fisheries Society, Vol. 90 (1), pp. 58-72.

Schrank, B.P., E.M. Dawley, and B. Ryan, 1997*. Evaluation of the effects of dissolved gas supersaturation on fish and invertebrates in Priest Rapids Reservoir, and downstream from Bonneville and Ice Harbor Dams, 1995*. National Marine Fisheries Service, Northwest Fisheries Science Center, Seattle, Washington, to U.S. Army Corps of Engineers, North Pacific Division, Portland, Oregon.

Schrank, B P., B.A. Ryan, and E.M. Dawley, 1996. E*ffects of dissolved gas supersaturation on fish residing in the Snake and Columbia rivers, 1996*. Annual Report 1996 of National Marine Fisheries Service, Northwest Fisheries Science Center, Seattle, Washington, to U.S. Department of Energy, Bonneville Power Administration, Portland, Oregon (Project 96-022).

Schrank, B.P., B.A. Ryan, and E.M. Dawley, 1998. E*ffects of dissolved gas supersaturation on fish residing in the Snake and Columbia rivers, 1996*. National Marine Fisheries Service, Northwest Fisheries Science Center, Seattle, Washington, to U.S. Army Corps of Engineers, North Pacific Division, Portland, Oregon.

Tanner, D.Q. and M.W. Johnston, 2001. D*ata-Collection Methods, Quality-Assurance Data, and Site Considerations for Total Dissolved Gas Monitoring, Lower Columbia River, Oregon and Washington, 2000.* Water-Resources Investigations Report 01–4005, U.S. Geological Survey, Portland, Oregon.

Toner, M.A., 1993. E*valuation of effects of dissolved gas supersaturation on fish and invertebrates downstream of Bonneville Dam, 1993*. National Marine Fisheries Service, Coastal Zone and Estuarine Studies Division, Northwest Fisheries Science Center, Seattle, Washington, to U.S. Army Corps of Engineers, North Pacific Division, Portland, Oregon.

Toner, M.A., B.A. Ryan, and E.M. Dawley, 1995. *Evaluation of the effects of dissolved gas supersaturation on fish and invertebrates downstream from Bonneville, Ice Harbor, and Priest Rapids Dams, 1994*. National Marine Fisheries Service, Northwest Fisheries Science Center, Seattle, Washington, to U.S. Army Corps of Engineers.

Urban, A.L., D. Johnson, and J.S. Gulliver, 2000. P*reliminary Model for Predicting Dissolved Gas Supersaturation at USACE Spillways on the Snake and Columbia Rivers.* Draft Technical Report. U.S. Army Corps of Engineers Waterways Experiment Station, Vicksburg, Mississippi.

USACE, 2000. *1999 Dissolved Gas Monitoring, Columbia River Basin.* U.S. Army Corps of Engineers, Northwest Division, Portland, Oregon.

USACE, 2001a. D*issolved Gas Abatement Study - Phase II Draft Final.* U.S. Army Corps of Engineers, Portland District and Walla Walla District.

USACE, 2001b. *Corps Of Engineers Plan Of Action For Dissolved Gas Monitoring In 2001.* U.S. Army Corps of Engineers, Northwest Division, Portland, Oregon.

USEPA, 2001. A*pplication of a 1-D Heat Budget Model to the Columbia River System.* U.S. States Environmental Protection Agency, Region 10, Seattle, Washington.

U.S. Water Resources Council, 1981. *Guidelines for Determining Flood Flow Frequency.* Bulletin #17B of the Hydrology Committee, Washington, D.C.

WDFW, ODFW, IDFG, and CRITFC, 1995. *Spill and 1995 risk management*. Washington Department of Fish and Wildlife, Oregon Department of Fish and Wildlife, Idaho Department of Fish and Game, and Columbia River Inter-Tribal Fish Commission.

Weitkamp, D.E., 1974. D*issolved gas supersaturation in the Columbia River system; salmonid bioassay and depth distribution studies, 1973 and 1974*. Parametrix, Inc., Utility Cooperative, Idaho Power Company, Boise, Idaho.

Weitkamp, D.E., 1976. D*issolved gas supersaturation: live cage bioassays at Rock Island Dam, Washington*. Pages 24-36 *in* D. F. Fiskeisen and M .J. Schneider, editors, Gas bubble disease. Technical Information Center, Energy Research and Development Administration, CONF-741033, Oak Ridge, Tennessee.

Weitkamp, D.E., and M. Katz, 1980. A *review of dissolved gas supersaturation literature*. Transactions of the American Fisheries Society 109:659-702.

Whitney, R.R., L. Calvin, M. Erho, and C. Coutant, 1997. D*ownstream passage for salmon at hydroelectric projects in the Columbia River Basin: development, installation, and evaluation*. U.S. Department of Energy, Northwest Power Planning Council, Report 97-15, Portland, Oregon.

Wilhelms, S.C., J. Carroll, and M.L. Schneider, 1997. *Workshop to Review Dissolved Gas Field Sampling Methods.* CEWES-CR-F Memorandum for Record dated 23 September 1997, U.S. Army Engineer Waterways Experiment Station, Vicksburg, Mississippi.

Wilhelms, S.C. and M.L. Schneider, 1998. D*ocumentation and Analysis of the Ice Harbor Near-Field Tailwater Study, March 1998, Post-Deflector Installation.* CEWES-CR-F Memorandum for Record dated 27 November 1998, U.S. Army Engineer Waterways Experiment Station, Vicksburg, Mississippi.